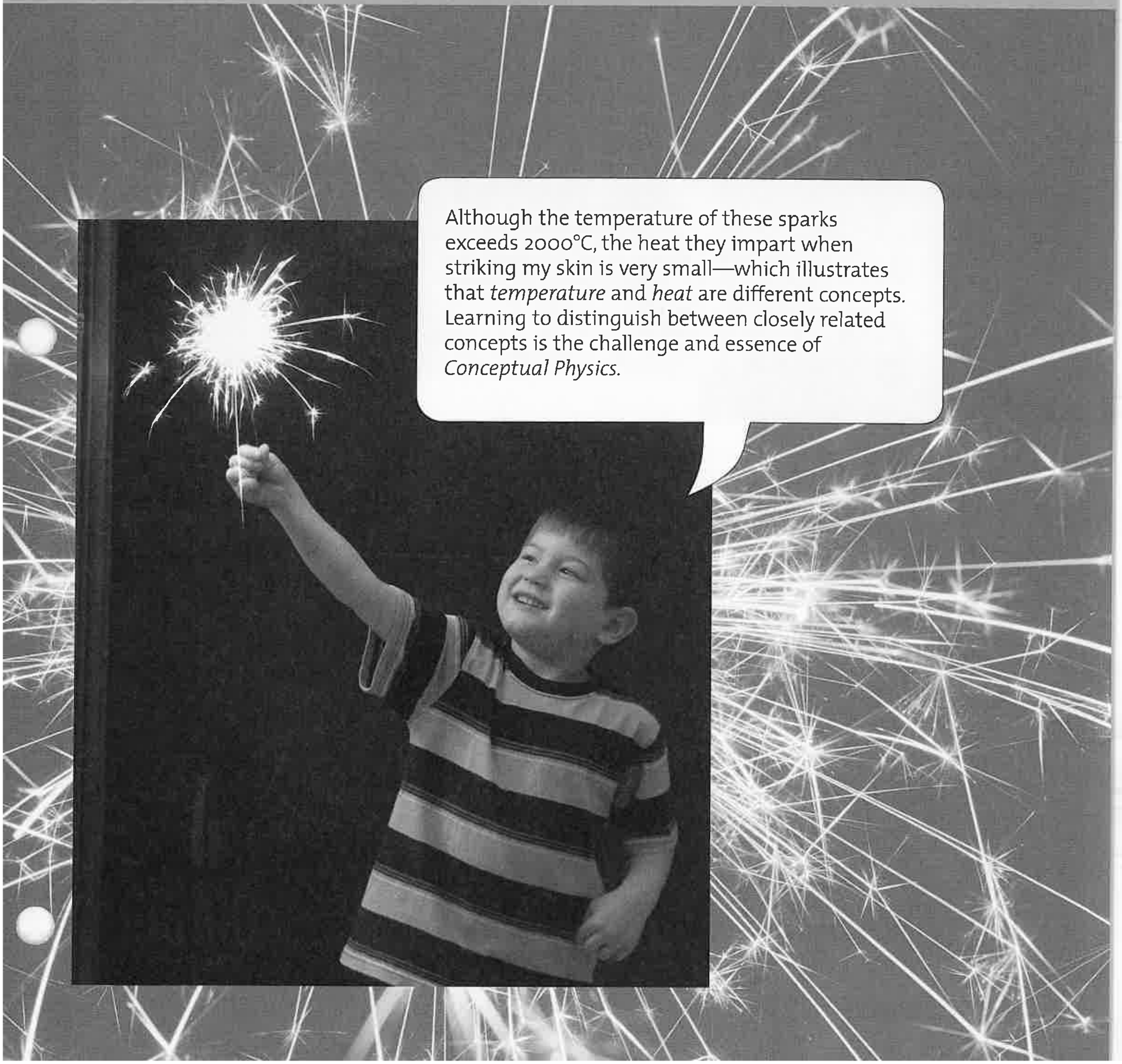
Part Three
Heat



Although the temperature of these sparks exceeds 2000°C, the heat they impart when striking my skin is very small—which illustrates that *temperature* and *heat* are different concepts. Learning to distinguish between closely related concepts is the challenge and essence of *Conceptual Physics.*

15 Temperature, Heat, and Expansion

1 Hot materials, such as lava and cinders bursting from a volcano, are composed of fast-moving atoms and molecules. 2 Anette Zetterberg asks her students to predict whether or not the ball can pass through the hole when the ring is heated. 3 A testament to Daniel Gabriel Fahrenheit is shown outside his home (now in Gdansk, Poland). 4 The six-sided structure of a snowflake is a result of the six-sided ice crystals that make it up.

I remember, as a child, that whenever my family drove past the Massachusetts Institute of Technology in Cambridge, a few miles from my home in Saugus, the name RUMFORD inscribed at the top of one of the prominent buildings was pointed out to me. I was told that our family is descended from this great scientist and diplomat.

Rumford was born Benjamin Thompson in Woburn, Massachusetts, in 1753. By age 13 he demonstrated unusual skill with mechanical devices and had an almost faultless command of language and grammar. Soon he was attending science lectures at Harvard University. At the age of 19 he became a schoolmaster in Concord (earlier called Rumford), New Hampshire. There he met and married a rich widow 14 years his senior. Then, during the outbreak of the American Revolution, he sided with those loyal to England, for a time spying on their behalf. Facing arrest in 1776, he abandoned his wife and daughter and fled just ahead of a mob armed with hot tar and bags of feathers. He made his way to Boston during the evacuation of British troops and caught a ship to England. Once there, his scientific career prospered. His experiments with gunpowder were so successful that at age 26 he was elected to the prestigious Royal Society. He eventually made his way to Bavaria, where he was made a count by the Bavarian prince for whom he was making cannons. He chose the name Count Rumford, after Rumford, New Hampshire.

A cannon is made by first casting a large metal cylinder in a foundry. The cylinder is then turned on a lathe, where the barrel is bored by advancing a stationary drill bit down the casting. Rumford's lathe was horse-driven, as was common at the time. Rumford was puzzled about the huge amounts of heat given off in the process. The notion of heat at the time, a hypothetical fluid called caloric, didn't fit the evidence. With a dull drill, the amount of heat was greater. As long as the horses kept at their work, more and more heat was produced. The source of heat was not something in the metal, but the motion of the horses. This discovery occurred long before friction was seen as a force, and before the concept of energy and its conservation were understood. Rumford's careful measurements convinced him of the falseness of the caloric theory of heat. Nevertheless, the caloric theory of heat as a fluid held sway for many years. Over time, his experiments were repeated and led to the connection between heat and work.

Rumford's achievements weren't limited to science. For example, while in Munich, he put unemployed beggars to work making uniforms for the Army. He also put them to work on public projects, one of which is now the famous English Gardens. A bronze statue of Count Rumford stands there as testimony of the gratitude of the citizens of Munich.

Rumford's many inventions made him a wealthy man. In 1796, he gave $5,000 each to the Royal Society of Great Britain and to the American Academy of Arts and Sciences to fund medals to be awarded every two years for outstanding scientific research on heat or light. Over the years, a galaxy of scientific stars in Europe and America have received the medals, including Michael Faraday, James Maxwell, Louis Pasteur, and Thomas Edison. The residue of Rumford's estate was left to Harvard University where it was used to establish the present Rumford Professorship.

Rumford was honored worldwide. In 1805 he wooed and married Madame Lavoisier, widow of Antoine Lavoisier. The marriage was brief and they soon separated. Rumford settled in Paris and continued his scientific work, extending the long list of his many inventions, until his death in 1814.

What an incredible relative!

Temperature

All matter—solid, liquid, and gas—is composed of continuously jiggling atoms or molecules. Because of this random motion, the atoms and molecules in matter have kinetic energy. The average kinetic energy of the individual particles produces an effect we can sense—warmth. The quantity that indicates warmth with respect to some standard is called **temperature.** The first "thermal meter" for measuring temperature, the *thermometer,* was invented by Galileo in 1602 (the word *thermal* is from the Greek term for "heat"). The once familiar mercury-in-glass thermometer came into widespread use some 70 years later. (Mercury thermometers are being phased out because of the danger of mercury poisoning.) We express the temperature of some quantity of matter by a number that corresponds to its degree of hotness or coldness on some chosen scale.

FIGURE 15.1
Can we trust our sense of hot and cold? Will both fingers feel the same temperature when placed in the warm water?

Nearly all materials expand when their temperature is raised and contract when their temperature is lowered. Most thermometers measure temperature by means of the expansion or contraction of a liquid, usually mercury or colored alcohol, in a glass tube with a scale.

On the most widely used temperature scale, the international scale, the number 0 is assigned to the temperature at which water freezes and the number 100 to the temperature at which water boils (at standard atmospheric pressure). The space between is divided into 100 equal parts called *degrees;* hence, a thermometer so calibrated has been called a *centigrade thermometer* (from *centi,* "hundredth," and *gradus,* "step"). However, it is now called a *Celsius thermometer* in honor of the man who first suggested the scale, the Swedish astronomer Anders Celsius (1701–1744).

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Another temperature scale is popular in the United States. On this scale, the number 32 is assigned to the temperature at which water freezes, and the number 212 is assigned to the temperature at which water boils. Such a scale makes up a Fahrenheit thermometer, named after its illustrious originator, the German physicist Gabriel Daniel Fahrenheit (1686–1736). The Fahrenheit scale will become obsolete if and when the United States goes metric.[1]

The temperature scale favored by scientists is the Kelvin scale, named after the Scottish physicist William Thomson, 1st Baron Kelvin (1824–1907). This scale is calibrated not in terms of the freezing and boiling points of water but in terms of energy itself. The number 0 is assigned to the lowest possible temperature—**absolute zero,** at which a substance has absolutely no kinetic energy to give up.[2] Absolute zero corresponds to −273°C on the Celsius scale. Units on the Kelvin scale have the same size increments as degrees on the Celsius scale, so the temperature of melting ice is 273 K. There are no negative numbers on the Kelvin scale. We won't treat this scale further until we study thermodynamics in Chapter 18.

Arithmetic formulas used for converting from Fahrenheit to Celsius, and vice versa, are popular in classroom exams. Such arithmetic exercises are not really physics, and the probability that you'll have the occasion to do this task elsewhere is small, so we will not be concerned with them here. Besides, this conversion can be very closely approximated by simply reading the corresponding temperature from the side-by-side scales in Figure 15.2.

Temperature is related to the random motion of atoms and molecules in a substance. (For brevity, hereafter in this chapter we'll simply say *molecules* to mean *atoms and molecules.*) More specifically, temperature is proportional to the average "translational" kinetic energy of random molecular motion (motion that carries the molecule from one place to another). Molecules may also rotate or vibrate, with associated rotational or vibrational kinetic energy—but these motions are not translational and don't define temperature.

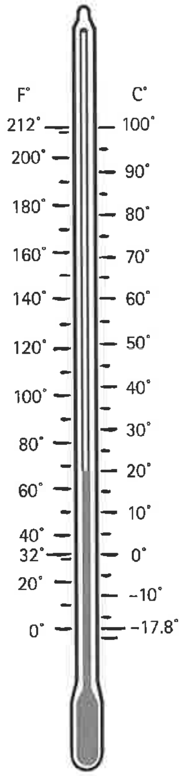

FIGURE 15.2

Fahrenheit and Celsius scales on a thermometer.

CHECK POINT

True or false? Temperature is a measure of the total kinetic energy in a substance.

Check Your Answer

False. Temperature is a measure of the *average* (not *total!*) translational kinetic energy of molecules in a substance. For example, there is twice as much total molecular kinetic energy in 2 L of boiling water as in 1 L—but the temperatures of the two volumes of water are the same because the *average* translational kinetic energy per molecule is the same in each.

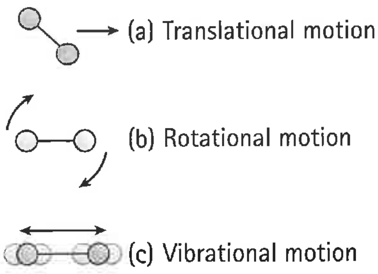

FIGURE 15.3

Particles in matter move in different ways. They move from one place to another, they rotate, and they vibrate to and fro. All these modes of motion, plus potential energy, contribute to the overall energy of a substance. Temperature, however, is defined by translational motion.

The effect of translational kinetic energy versus rotational and vibrational kinetic energy is dramatically demonstrated by a microwave oven. The microwaves that

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[1] The conversion to Celsius would put the United States in step with the rest of the world, where the Celsius scale is the standard. Americans are slow to convert. Changing any long-established custom is difficult, and the Fahrenheit scale does have some advantages in everyday use. For example, its degrees are smaller (1°F = 5/9°C), which gives greater accuracy when reporting the weather in whole-number temperature readings. Then, too, people somehow attribute a special significance to numbers increasing by an extra digit. Thus, when the temperature of a hot day is reported to reach 100°F, the idea of heat is conveyed more dramatically than by stating that the temperature is 38°C. Like so much of the British system of measure, the Fahrenheit scale is geared to human beings.

[2] Even at absolute zero, a substance has what is called "zero-point energy," which is unavailable energy that cannot be transferred to a different substance. Helium, for example, has enough motion at absolute zero to avoid freezing. The explanation for this involves quantum theory.

bombard your food cause certain molecules in the food, mainly water molecules, to flip to and fro and to oscillate with considerable rotational kinetic energy. But oscillating molecules don't cook food. What does raise the temperature and cook the food, and swiftly, is the translational kinetic energy imparted to neighboring molecules that are bounced off the oscillating water molecules. (To picture this, imagine a bunch of marbles set flying in all directions after encountering the spinning blades of a fan—also, see page 398.) If neighboring molecules didn't interact with the oscillating water molecules, the temperature of the food would be no different than before the microwave oven was turned on.

Interestingly, what a thermometer really displays is its *own* temperature. When a thermometer is in thermal contact with something whose temperature we wish to know, energy will flow between the two until their temperatures are equal and thermal equilibrium is established. If we know the temperature of the thermometer, we then know the temperature of what is being measured. A thermometer should be small enough that it doesn't appreciably alter the temperature of what is being measured. If you are measuring the air temperature of a room, then your thermometer is small enough. But, if you are measuring the temperature of a drop of water, contact between the drop and the thermometer may change the drop's temperature—a classic case of the measuring process changing the thing that is being measured.

Heat

If you touch a hot stove, energy enters your hand because the stove is warmer than your hand. When you touch a piece of ice, however, energy transfers from your hand into the colder ice. The direction of spontaneous energy transfer is always from a warmer object to a neighboring cooler object. The energy transferred from one object to another because of a temperature difference between them is called **heat.**

It is important to point out that matter does not *contain* heat. This was discovered by Rumford in his cannon-boring experiments, as mentioned earlier. Rumford, and investigators that followed, realized that matter contains molecular kinetic energy and possibly potential energy, *not heat.* Heat is *energy in transit* from a body of higher temperature to one of lower temperature. Once transferred, the energy ceases to be heat. (As an analogy, work is also energy in transit. A body does not *contain* work. It *does* work or has work done on it.) In previous chapters, we called the energy resulting from heat flow *thermal energy* to make clear its link to heat and temperature. In this chapter, we will use the term that scientists prefer, *internal energy.*

FIGURE 15.4

There is more molecular kinetic energy in the container filled with warm water than in the small cupful of higher-temperature water.

Internal energy is the grand total of all energies inside a substance. In addition to the translational kinetic energy of jostling molecules in a substance, there is energy in other forms. There is rotational kinetic energy of molecules and kinetic energy due to internal movements of atoms within molecules. There is also potential energy due to the forces between molecules. So a substance does not contain heat—it contains internal energy.

When a substance absorbs or gives off heat, the internal energy of the substance increases or decreases. In some cases, as when ice is melting, the added heat does not increase molecular kinetic energy but goes instead into other forms of energy. The substance undergoes a change of phase, which we will cover in detail in Chapter 17.

For two things in thermal contact, heat flow is from the higher-temperature substance to the lower-temperature substance. This is not necessarily a flow from a

Just as dark is the absence of light, cold is the absence of internal energy.

substance with more internal energy to a substance with less internal energy. There is more internal energy in a bowl of warm water than there is in a red-hot thumbtack; yet, if the tack is immersed in the water, heat flows from the hot tack to the warm water and not the other way around. Heat never flows of itself from a lower-temperature substance into a higher-temperature substance.

How much heat flows depends not only on the temperature difference between substances but on the amount of material as well. For example, a barrelful of hot water will transfer more heat to a cooler substance than will a cupful of water. There is more internal energy in the larger volume of water.

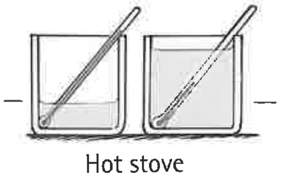

FIGURE 15.5

Although the same quantity of heat is added to both containers, the temperature increases more in the container with the smaller amount of water.

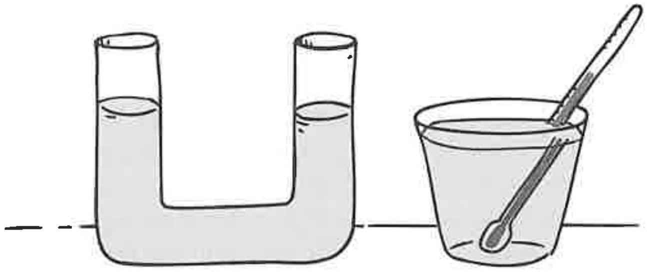

FIGURE 15.6

Just as water in the two arms of the U-tube seeks a common level (where the pressures at any given depth are the same), the thermometer and its immediate surroundings reach a common temperature (at which the average molecular KE is the same for both).

CHECK POINT

1. Suppose you apply a flame to 1 L of water for a certain time and its temperature rises by 2°C. If you apply the same flame for the same time to 2 L of water, by how much will its temperature rise?
2. If a fast marble hits a random scatter of slow marbles, does the fast marble usually speed up or slow down? Which lose(s) kinetic energy and which gain(s) kinetic energy—the initially fast-moving marble or the initially slow ones? How do these questions relate to the direction of heat flow?

Check Your Answers

1. Its temperature will rise by only 1°C, because there are twice as many molecules in 2 L of water, and each molecule receives only half as much energy on the average.
2. A fast-moving marble slows when it hits slower-moving marbles. It transfers some of its kinetic energy to the slower ones. Likewise with the flow of heat. Molecules with more kinetic energy that are in contact with molecules having less kinetic energy transfer some of their excess energy to the less energetic ones. The direction of energy transfer is from hot to cold. For both the marbles and the molecules, however, the *total* energy before and after contact is the same.

Temperature is measured in degrees; heat is measured in joules.

MEASURING HEAT

So heat is the flow of energy from one thing to another due to a temperature difference. Since heat energy is in transit, it is measured in joules. In the United States, a more common unit of heat is the *calorie*. The calorie is defined as the amount of heat required to change the temperature of 1 gram of water by 1 Celsius degree.[3]

The energy ratings of foods and fuels are determined by burning them and measuring the energy released. (Your body "burns" food at a slow rate.) The heat unit used to label foods is actually the kilocalorie, which is 1000 calories (the heat required to raise the temperature of 1 kilogram of water by 1°C). To distinguish this unit from the smaller calorie, the food unit is sometimes called a *Calorie* (written with a capital *C*). It is important to remember that the calorie and Calorie are units of energy. These names are historical carryovers from the early idea that heat is an

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[3] A less common unit of heat is the British thermal unit (BTU). The BTU is defined as the amount of heat required to change the temperature of 1 lb of water by 1 Fahrenheit degree. One BTU equals 1054 J.

invisible fluid called *caloric*. This view persisted, even after Rumford's experiments to the contrary, into the 19th century.

We now know that heat is a form of energy transfer, not a separate substance, so it doesn't need its own separate unit. Someday the calorie may give way to the joule, an SI unit, as the common unit for measuring heat. (The relationship between calories and joules is that 1 calorie = 4.184 joules.) In this book, we'll learn about heat with the conceptually simpler calorie—but, in the lab, you may use the joule equivalent, where an input of 4.184 joules raises the temperature of 1 gram of water by 1°C.

FIGURE 15.7

To the weight watcher, the peanut contains 10 Calories; to the physicist, it releases 10,000 calories (or 41,840 joules) of energy when burned or consumed.

CHECK POINT

An iron thumbtack and a big iron bolt are removed from a hot oven. Both are red-hot and have the same temperature. When dropped into identical containers of water of equal temperature, which one raises the water temperature more?

Check Your Answer

The big iron bolt has more internal energy to impart to the water and warms it more than the thumbtack. Although they have the same initial temperature (the same *average* kinetic energy per molecule), the more massive bolt has more molecules and therefore more *total* energy—internal energy. This example underscores the difference between temperature and internal energy.

Both heat and work are ways in which energy can be transferred from one substance to another. Although they are measured in joules, they shouldn't be confused with energy itself.

Specific Heat Capacity

You've likely noticed that some foods remain hotter much longer than others do. If you remove a piece of toast from a toaster and pour hot soup into a bowl at the same time, a few minutes later the soup is still pleasantly warm, while the toast has cooled off considerably. Similarly, if you wait a short while before eating a slice of hot roast beef and a scoop of mashed potatoes, both initially at the same temperature, you'll find that the meat has cooled off more than the potatoes.

Different substances have different capacities for storing internal energy. If we heat a pot of water on a stove, we might find that it requires 15 minutes to raise it from room temperature to its boiling temperature. But if we put an equal mass of iron on the same flame, we would find that it would rise through the same temperature range in only about 2 minutes. For silver, the time would be less than a minute.

FIGURE 15.8

The filling of hot apple pie may be too hot to eat even though the crust is not.

Different materials require different quantities of heat to raise the temperature of a given mass of the material by a specified number of degrees. This is partly due to different materials absorbing energy in different ways. The energy may be spread around among several kinds of energy, including molecular rotation and potential energy, which raises the temperature less. Except for special cases such as helium gas, the energy is always shared among different kinds of motion, but in varying degrees.

Whereas 1 gram of water requires 1 calorie of energy to raise its temperature 1 Celsius degree, it takes only about one-eighth as much energy to raise the temperature of a gram of iron by the same amount. Water absorbs more heat per gram than iron for the same change in temperature. We say water has a higher **specific heat capacity** (sometimes simply called *specific heat*).[4]

The specific heat capacity of any substance is defined as the quantity of heat required to change the temperature of a unit mass of the substance by 1 degree.

If you add 1 calorie of heat to 1 gram of water, you'll raise its temperature by 1°C.

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[4] If we know the specific heat capacity c, the formula for the quantity of heat Q involved when a mass m of a substance undergoes a change in temperature ΔT is $Q = cm\Delta T$. Or, heat transferred = specific heat capacity × mass × temperature change.

We can think of specific heat capacity as thermal inertia. Recall that inertia is a term used in mechanics to signify the resistance of an object to a change in its state of motion. Specific heat capacity is a sort of thermal inertia since it signifies the resistance of a substance to a change in its temperature.

THE HIGH SPECIFIC HEAT CAPACITY OF WATER

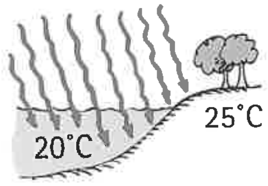

FIGURE 15.9

Because water has a high specific heat capacity and is transparent, it takes more energy to warm the water than to warm the land. Solar energy incident on the land is concentrated at the surface, but because sunlight on water extends beneath the surface, it is "diluted."

Water has a much higher capacity for storing energy than all but a few uncommon materials. A relatively small amount of water absorbs a large quantity of heat for a correspondingly small temperature rise. Because of this, water is a very useful cooling agent in the cooling systems of automobiles and other engines. If a liquid of lower specific heat capacity were used in cooling systems, its temperature would rise higher for a comparable absorption of heat.

Water also takes a long time to cool, a fact that explains why, in previous times, hot-water bottles were employed on cold winter nights. In many places, electric blankets have replaced them. This tendency on the part of water to resist changes in temperature improves the climate in many locations. The next time you are looking at a world globe, notice the high latitude of Europe. If water did not have a high specific heat capacity, the countries of Europe would be as cold as the northeastern regions of Canada, for both Europe and Canada receive about the same amount of sunlight per square kilometer. The Atlantic current known as the Gulf Stream carries warm water northeast from the Caribbean. It retains much of its internal energy long enough to reach the North Atlantic off the coast of Europe, where it then cools. The energy released, about 1 calorie per degree for each gram of water that cools, transfers to the air, where it is carried by the westerly winds over the European continent.

Climate is about average behavior while weather is about the fluctuations. Climate is what we expect and weather is what we get.

A similar effect occurs in the United States. The winds in the latitudes of North America are westerly. On the West Coast, air moves from the Pacific Ocean to the land. Because of water's high specific heat capacity, an ocean does not vary much in temperature from summer to winter. The water is warmer than the air in the winter and cooler than the air in the summer. In winter, the water warms the air that moves over it, and the air warms the coastal regions of North America. In summer, the water cools the air, and the coastal regions are cooled. On the East Coast, air moves from the land to the Atlantic Ocean. Land, with a lower specific heat capacity, gets hot in the summer but cools rapidly in the winter. As a result of water's high specific heat capacity and the wind directions, the West Coast city of San Francisco is

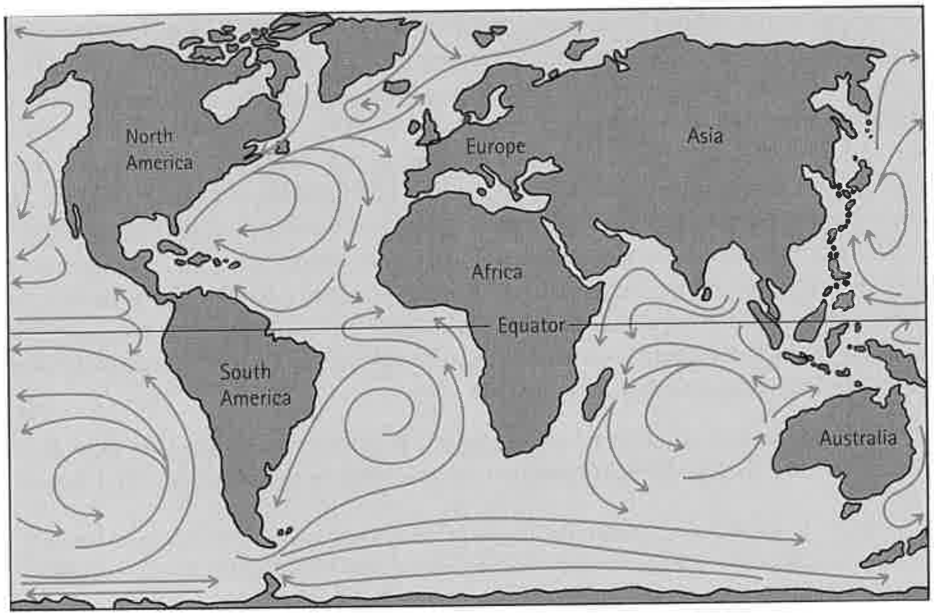

FIGURE 15.10

Many ocean currents, shown in blue, distribute heat from the warmer equatorial regions to the colder polar regions.

warmer in the winter and cooler in the summer than the East Coast city of Washington, D.C., which is at about the same latitude.

Islands and peninsulas that are more or less surrounded by water do not have the same extremes of temperatures that are observed in the interior of a continent. When air is hot in summer months, water cools it. When air is cold in winter months, water warms it. Water moderates temperature extremes. The high summer and low winter temperatures common in Manitoba and the Dakotas, for example, are largely due to the absence of large bodies of water. Europeans, islanders, and people living near ocean air currents should be glad that water has such a high specific heat capacity. San Franciscans are!

FIGURE 15.11

The temperature of the sparks is very high, about 2000°C. That's a lot of energy per molecule of spark. Because of the few molecules per spark, however, internal energy is safely small. Temperature is one thing; transfer of energy is another.

CHECK POINT

Which has a higher specific heat capacity, water or sand?

Check Your Answer

Water has a higher specific heat capacity. Water has more thermal inertia and takes a longer time to warm in the hot sunlight and a longer time to cool on a cold night. Sand has a low heat capacity, as evidenced by how quickly the surface warms in the morning sunlight and how quickly it cools at night. (Walking or running barefoot across scorching sand in the daytime is a much different experience than walking on cool sand in the evening.)

Thermal Expansion

When the temperature of a substance is increased, its molecules or atoms jiggle faster and move farther apart, on the average. The result is an expansion of the substance. With few exceptions, all forms of matter—solids, liquids, gases, and plasmas—generally expand when they are heated and contract when they are cooled.

In most cases involving solids, these changes in volume are not very noticeable, but careful observation usually detects them. Telephone wires become longer and sag more on a hot summer day than on a cold winter day. A metal lid on a glass jar can often be loosened by heating the lid under hot water. If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the resulting expansion or contraction may break the glass, especially if the glass is thick. Pyrex heat-resistant glassware is an exception because it's specially formulated to expand very little with increasing temperature (about a third as much as ordinary glass).

FIGURE 15.12

One end of the bridge is fixed, while the end shown rides on rockers to allow for thermal expansion.

The expansion of substances must be accommodated in structures and devices of all kinds. A dentist uses filling material that has the same rate of expansion as teeth. The aluminum pistons of some automobile engines are just a bit smaller in diameter than the steel cylinders to allow for the much greater expansion rate of aluminum. Civil engineers use reinforcing steel with the same expansion rate as concrete. Long steel bridges commonly have one end fixed while the other end rests on rockers (Figure 15.12). The Golden Gate Bridge in San Francisco contracts more than a meter in cold weather. The roadway itself is segmented with tongue-and-groove–type gaps called *expansion joints* (Figure 15.13). Similarly, concrete roadways and sidewalks are intersected by gaps, sometimes filled with tar, so that the concrete can expand freely in summer and contract in winter.

In times past, railroad tracks were laid in 39-foot segments connected by joint bars, with gaps for thermal expansion. In summer months, the tracks expanded and the gaps were narrow. In winter, the gaps widened, which was responsible for a more

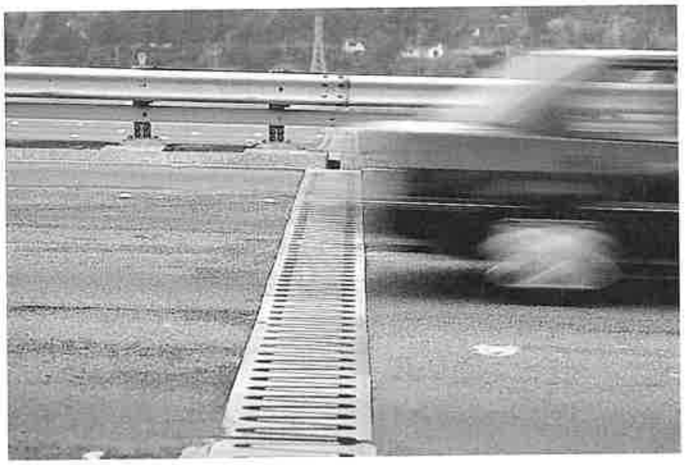

FIGURE 15.13

This gap in the roadway of a bridge is called an expansion joint; it allows the bridge to expand and contract.

pronounced clickity-clack when the trains rolled along the tracks. We don't hear clickity-clacks these days because someone got the bright idea to eliminate the gaps by welding the tracks together. Doesn't expansion in the summer heat cause the welded tracks to buckle, as shown in Figure 15.14? Not if the tracks are laid and welded on the hottest summer days! Track shrinkage on cold winter days stretches the tracks, which doesn't cause buckling. Stretched tracks are okay.

FIGURE 15.14

Thermal expansion. The extreme heat of a July day in Asbury Park, New Jersey, caused the buckling of these railroad tracks. *(Wide World Photos)*

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How a Thermostat Works

Different substances expand at different rates. When two strips of different metals—say, one of brass and the other of iron—are welded or riveted together, the greater expansion of one metal results in the bending of the strip, as shown in Figure 15.15. Such a compound thin bar is called a *bimetallic strip.* When the strip is heated, one side of the double strip becomes longer than the other, causing the strip to bend into a curve. On the other hand, when the strip is cooled, it tends to bend in the opposite direction, because the metal that expands more also shrinks more. The movement of the strip may be used to turn a pointer, regulate a valve, or close a switch. Bimetallic strips are used in oven thermometers, electric toasters, and a variety of devices.

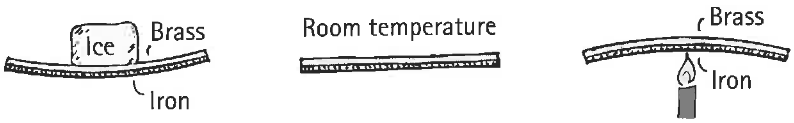


FIGURE 15.15

A bimetallic strip. Brass expands more when heated than iron does and contracts more when cooled. Because of this behavior, the strip bends as shown.

A practical application of different rates of expansion is the thermostat (Figure 15.16). The back-and-forth bending of the bimetallic coil opens and closes an electric circuit. When the room becomes too cold, the coil bends toward the brass side, which activates an electrical switch that turns on the heat. When the room becomes too warm, the coil bends toward the iron side, which activates an electrical switch that turns off the heating unit. Refrigerators are equipped with thermostats to prevent them from becoming either too warm or too cold.

Liquids expand appreciably with increases in temperature. In most cases, the expansion of liquids is greater than the expansion of solids. The gasoline overflowing a car's tank on a hot day is evidence for this. If the tank and contents expanded at the same rate, they would expand together and no overflow would occur. Similarly, if the expansion of the glass of a thermometer were as great as the expansion of the mercury, the mercury would not rise with increasing temperature. The reason the mercury in a thermometer rises with increasing temperature is that the expansion of liquid mercury is greater than the expansion of glass.

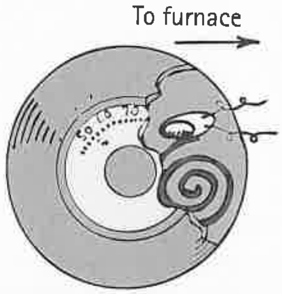


FIGURE 15.16

A thermostat. When the bimetallic coil expands, the drop of liquid mercury rolls away from the electrical contacts and breaks the electrical circuit. When the coil contracts, the mercury rolls against the contacts and completes the circuit.

CHECK POINT

Why is it advisable to allow telephone lines to sag when stringing them between poles in summer?

Check Your Answer

Telephone lines are longer in summer, when they are warmer, and shorter in winter, when they are cooler. They therefore sag more on hot summer days than in winter. If the telephone lines are not strung with enough sag in summer, they might contract too much and snap during the winter.

FIGURE 15.17

Place a dented Ping-Pong ball in boiling water, and you'll remove the dent. Why?

EXPANSION OF WATER

Water, like most other substances, expands when heated. But, interestingly, it *doesn't* expand in the temperature range between 0°C and 4°C. Something quite fascinating happens in this range. Ice has a crystalline structure, with open-structured crystals. Water molecules in this open structure occupy a greater volume than in the liquid phase (Figure 15.18). This means that ice is less dense than water.

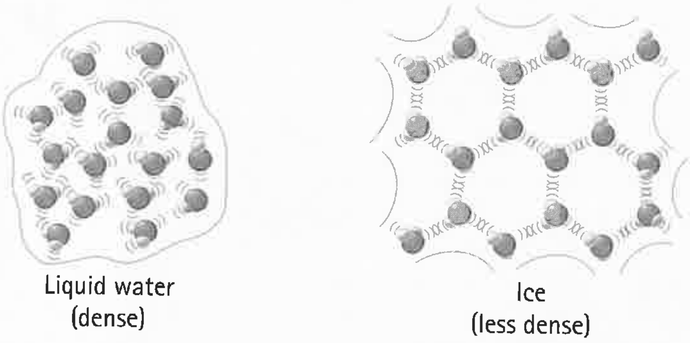


FIGURE 15.18

Liquid water is more dense than ice because water molecules in a liquid are closer together than water molecules frozen in ice, where they have an open crystalline structure.

CHECK POINT

What's inside the open spaces of the water crystals shown in Figure 15.18? Is it air, water vapor, or nothing?

Check Your Answer

There's nothing at all in the open spaces. It's empty space—a void. If there were air or vapor in the open spaces, the illustration should show molecules there—oxygen and nitrogen for air and H_2O for water vapor.

fyi

- Snowflakes form mainly from water vapor rather than liquid water. Truly symmetrical snowflakes are the exception, rather than the rule. Many mechanisms interrupt perfect snowflake growth. In 1611, the astronomer Kepler wrote a paper on six-cornered snowflakes. Fifty-four years later, physicist Robert Hooke used his early microscope to sketch the forms of snowflakes.

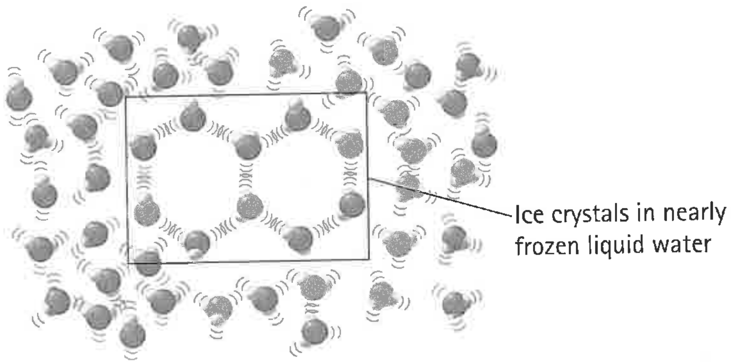
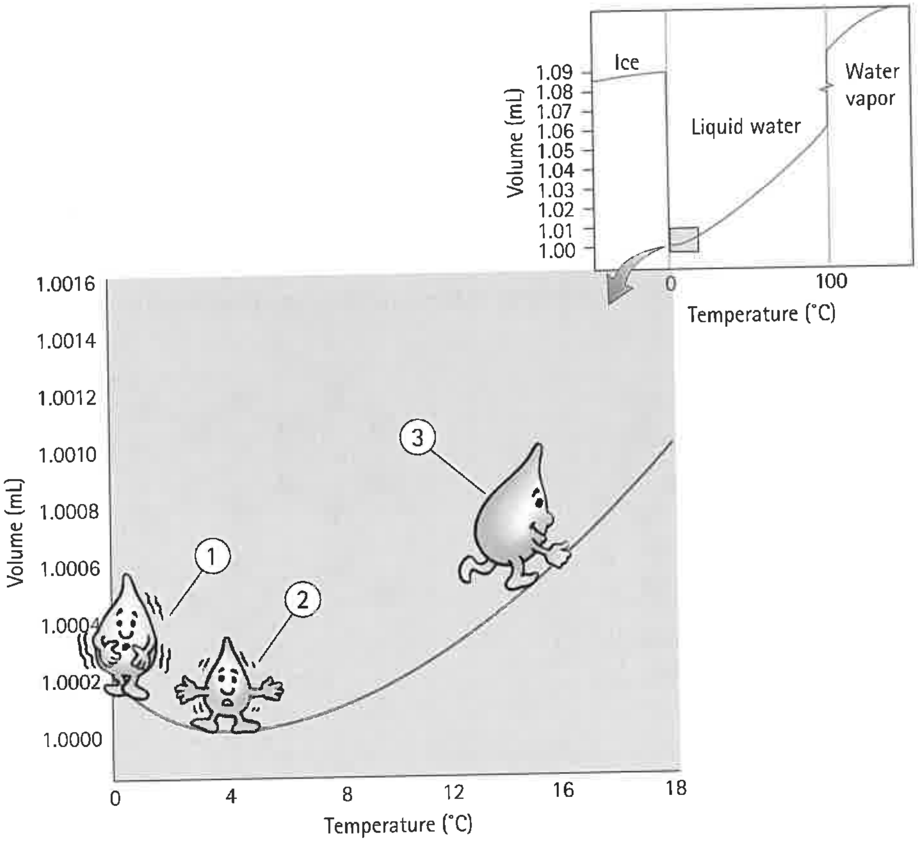


FIGURE 15.19
Close to 0°C, liquid water contains crystals of ice. The open structure of these 3-D cagelike crystals increases the volume of the water slightly.

When ice melts, not all the open-structured crystals collapse. Some microscopic crystals remain in the ice-water mixture, making up a microscopic slush that slightly "bloats" the water, increasing its volume slightly (Figure 15.19). This results in ice water being less dense than slightly warmer water. As the temperature of water at 0°C is increased, more of the remaining ice crystals collapse. The melting of these crystals further decreases the volume of the water. The water undergoes two processes at the same time—contraction and expansion. Volume tends to decrease as ice crystals collapse, while volume tends to increase due to greater molecular motion. The collapsing effect dominates until the temperature reaches 4°C. After

fyi

- How does rock salt spread on icy roads in winter help to melt ice? It so happens that salt in water separates into sodium and chlorine ions, which when joining water molecules, give off energy that melts microscopic parts of an icy surface. The pressure of automobiles rolling along the salt-covered icy surface forces the salt into the ice, enhancing the melting process. The only difference between the rock salt and the salt you sprinkle on popcorn is the size of the crystals.



① Liquid water below 4°C is bloated with ice crystals.

② Upon warming, the crystals collapse, resulting in a smaller volume for the liquid water.

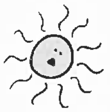
③ Above 4°C, liquid water expands as it is heated because of greater molecular motion.

FIGURE 15.20
Between 0°C and 4°C, the volume of liquid water decreases as temperature increases. Above 4°C, water behaves the way other substances do: Its volume increases as its temperature increases. The volumes shown here are for a 1-gram sample.

Life at the Extremes

Some deserts, such as those on the plains of Spain, the Sahara in Africa, and the Gobi Desert in central Asia, reach surface temperatures of 60°C (140°F). Too hot for life? Not for certain species of ants of the genus Cataglyphis, which thrive at this searing temperature. At this extremely high temperature, the desert ants can forage for food without the presence of lizards, which would otherwise prey upon them. Resistant to heat, these ants can withstand higher temperatures than any other creatures in the desert (except microbes). How they are able to do this is currently being researched. They scavenge the desert surface for the corpses of those creatures that did not find cover in time, touching the hot sand as little as possible while often sprinting on four legs with two held high in the air. Although their foraging paths zigzag over the desert floor, their return paths are almost straight lines to their nest holes. They attain speeds of 100 body lengths per second. During an average 6-day life, most of these ants retrieve 15 to 20 times their weight in food.

From deserts to glaciers, a variety of creatures have invented ways to survive the harshest corners of the world. A species of worm thrives in the glacial ice in the Arctic. There are insects in the Antarctic ice that pump their bodies full of antifreeze to ward off becoming frozen solid. Some fish that live beneath the ice are able to do the same. Then there are bacteria that thrive in boiling hot springs as a result of having heat-resistant proteins.



An understanding of how creatures survive at the extremes of temperature can provide clues for practical solutions to the physical challenges faced by humans. Astronauts who venture from Earth, for example, will need all the techniques available for coping with unfamiliar environments.

that, expansion overrides contraction, because most of the microscopic ice crystals have melted by then (Figure 15.20).

When ice water freezes to become solid ice, its volume increases by nearly 10% and its density is lowered. That's why ice floats on water. Like most other substances, solid ice contracts with further cooling. This behavior of water is very important in nature. If water were most dense at 0°C, it would settle to the bottom of a pond or lake. Water at 0°C, however, is less dense and "floats" at the surface. That's why ice forms at the surface.

So a pond freezes from the surface downward. In a cold winter, the ice will be thicker than in a milder winter. Water at the bottom of an ice-covered pond is 4°C, which is relatively warm for the organisms that live there. Interestingly, very deep bodies of water are not ice covered even in the coldest of winters. This is because all the water must be cooled to 4°C before lower temperatures can be reached. For deep water, the winter is not long enough to reduce an entire pond to 4°C. Any 4°C water lies at the bottom. Because of water's high specific heat capacity and poor ability to conduct heat, the bottom of a deep body of water in a cold region remains at a constant 4°C year-round. Fish should be glad that this is so.

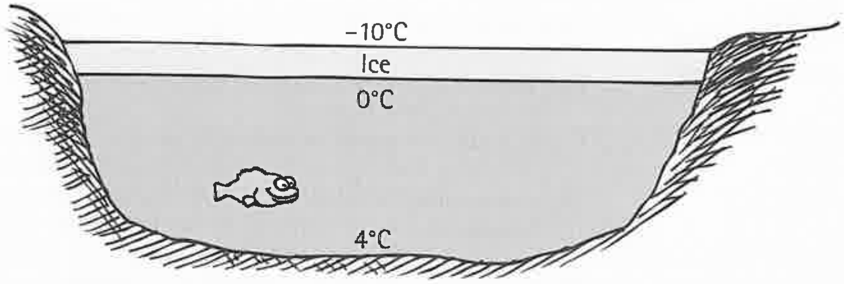


FIGURE 15.21

As water is cooled at the surface, it sinks until the temperature of the entire lake is 4°C. Only then can the surface water cool to 0°C without sinking. Once ice has formed, temperatures lower than 4°C can extend down into the lake.

CHECK POINT

1. What was the precise temperature at the bottom of Lake Michigan, where the water is deep and the winters long, on New Year's Eve in 1901?
2. Why do fish benefit from water being most dense at 4°C?

Check Your Answers

1. 4°C, because the temperature at the bottom of any body of water containing any 4°C water has a bottom temperature of 4°C, for the same reason that rocks are at the bottom. Rocks are more dense than water, and 4°C water is more dense than water at any other temperature. So both rocks and 4°C water sink to the bottom. Water is also a poor heat conductor, so if the body of water is deep and in a region of long winters and short summers, the water at the bottom likely remains a constant 4°C year-round.
2. Since water is most dense at 4°C, colder water rises and freezes on the surface, which means that fish remain in relative warmth!

SUMMARY OF TERMS

Temperature A measure of the average translational kinetic energy per molecule in a substance, measured in degrees Celsius or Fahrenheit or in kelvins (K).

Absolute zero The lowest possible temperature that a substance may have—the temperature at which molecules of the substance have their minimum kinetic energy.

Heat The energy that flows from a substance of higher temperature to a substance of lower temperature, commonly measured in calories or joules.

Internal energy The total of all molecular energies, kinetic plus potential, that are internal to a substance.

Specific heat capacity The quantity of heat per unit mass required to raise the temperature of a substance by 1 Celsius degree.

REVIEW QUESTIONS

1. Why does a penny become warmer when it is struck by a hammer?

Temperature

2. What are the temperatures for freezing water on the Celsius and Fahrenheit scales? For boiling water?
3. What are the temperatures for freezing water and boiling water on the Kelvin temperature scale?
4. What is meant by "translational" kinetic energy?
5. Which defines temperature—translational kinetic energy, rotational kinetic energy, vibrational kinetic energy, or all of these?
6. What is meant by the statement that a thermometer measures its own temperature?

Heat

7. When you touch a cold surface, does cold travel from the surface to your hand or does energy travel from your hand to the cold surface? Explain.
8. Distinguish between temperature and heat.
9. Distinguish between heat and internal energy.
10. What determines the direction of heat flow?

Measuring Heat

11. How is the energy value of foods determined?
12. Distinguish between a calorie and a Calorie.
13. Distinguish between a calorie and a joule.

Specific Heat Capacity

14. Which warms up faster when heat is applied—iron or silver?
15. Does a substance that heats up quickly have a high or a low specific heat capacity?
16. Does a substance that cools off quickly have a high or a low specific heat capacity?
17. How does the specific heat capacity of water compare with the specific heat capacities of other common materials?
18. Northeastern Canada and much of Europe receive about the same amount of sunlight per unit area. Why, then, is Europe generally warmer in the winter?
19. According to the law of conservation of energy, if ocean water cools, something else should warm. What is it that warms?
20. Why is the temperature fairly constant for land masses surrounded by large bodies of water?

Thermal Expansion

21. Why do substances expand when temperature is increased?
22. Why does a bimetallic strip bend with changes in temperature?
23. Which generally expands more for an equal increase in temperature—solids or liquids?

Expansion of Water

24. When the temperature of ice-cold water is increased slightly, does it undergo a net expansion or a net contraction?
25. What is the reason for ice being less dense than water?
26. Does "microscopic slush" in water tend to make it more dense or less dense?
27. What happens to the amount of "microscopic slush" in cold water when its temperature is increased?
28. At what temperature do the combined effects of contraction and expansion produce the smallest volume for water?
29. Why does all the water in a lake have to be cooled to 4°C before surface water can be cooled below 4°C?
30. Why does ice form at the surface of a body of water instead of at the bottom?

PROJECT

Write a letter to Grandpa describing how you're learning to see the connections in nature. Also give him examples of how you're learning to distinguish between closely related ideas. Use temperature and heat as examples.

EXERCISES

1. In a meeting room, there are chairs, a table, and people. Which of these things has a temperature (a) lower than, (b) greater than, or (c) equal to the temperature of the air?
2. Which is greater—an increase in temperature of 1 Celsius degree or an increase of 1 Fahrenheit degree?
3. In a glass of water at room temperature, do all the molecules have the same speed?
4. Why wouldn't you expect all the molecules in a gas to have the same speed?
5. Why can't you establish whether you are running a high temperature by touching your own forehead?
6. Which has more kinetic energy—a molecule in a gram of ice water or a molecule in a gram of steam? Defend your answer.
7. Which has the greater amount of internal energy—an iceberg or a cup of hot coffee? Defend your answer.
8. When a mercury thermometer is heated, the mercury expands and rises in the thin tube of glass. What does this indicate about the relative rates of expansion for mercury and glass? What would happen if their expansion rates were the same?
9. Which is the largest unit of heat transfer—Calorie, calorie, or joule?
10. If you drop a hot rock into a pail of water, the temperature of the rock and the water will change until both are equal. The rock will cool and the water will warm. Does this hold true if the hot rock is dropped into the Atlantic Ocean? Explain.
11. Consider two glasses, one filled with water and the other half-full, with the water in the two glasses being at the same temperature. In which glass are the water molecules moving faster? In which is there greater internal energy? In which will more heat be required to increase the temperature by 1°C?
12. Would you expect the temperature of water at the bottom of Niagara Falls to be slightly higher than the temperature at the top of the falls? Why?
13. Thermometers in a physics lab often use gas rather than mercury. Whereas changes in volume indicate temperature in a mercury thermometer, what changes in a gas do you think indicate temperature in a gas thermometer?
14. Why does the pressure of gas enclosed in a rigid container increase as the temperature increases?
15. Adding the same amount of heat to two different objects does not necessarily produce the same increase in temperature. Why not?
16. A certain quantity of heat is supplied to both a kilogram of water and to a kilogram of iron. Which undergoes the greater change in temperature? Defend your answer.
17. Which has the greater specific heat capacity—an object that cools quickly, or an object of the same mass that cools more slowly?
18. If the specific heat capacity of water were less, would a nice hot bath be a longer or a shorter experience?
19. Heat added to a substance goes partly into the translational kinetic energy of its molecules, which directly elevates temperature. For some substances, large proportions of heat also go into vibrations and rotations of the molecules. Would you expect materials in which a lot of energy goes into nontranslational molecular motions to have a high or a low specific heat capacity? Defend your answer.
20. Why does a piece of watermelon stay cool for a longer time than sandwiches do when both are removed from a picnic cooler on a hot day?
21. Ethyl alcohol has about one-half the specific heat capacity of water. If equal masses of each at the same temperature are supplied with equal quantities of heat, which will undergo the greater change in temperature?
22. When a 1-kg metal pan containing 1 kg of cold water is removed from the refrigerator and set on a table, which absorbs more heat from the room—the pan or the water?
23. In times past, on a cold winter night, it was common to bring a hot object to bed with you. Which would keep

you warmer through the cold night—a 10-kg iron brick or a 10-kg jug of hot water at the same temperature? Explain.

24. Bermuda is about as far north of the equator as North Carolina, but, unlike North Carolina, it has a subtropical climate year-round. Why is this so?

25. Iceland, so named to discourage conquest by expanding empires, is not at all ice covered like Greenland and parts of Siberia, even though it is not far from the Arctic Circle. The average winter temperature of Iceland is considerably higher than it is in regions at the same latitude in eastern Greenland and central Siberia. Why is this so?

26. Why does the presence of large bodies of water tend to moderate the climate of nearby land—to make it warmer in cold weather and cooler in hot weather?

27. If the winds at the latitude of San Francisco and Washington, D.C., were from the east rather than from the west, why might San Francisco be able to grow only cherry trees and Washington, D.C., both cherry trees and palm trees?

28. Desert sand is very hot in the day and very cool at night. What does this indicate about its specific heat capacity?

29. Cite an exception to the claim that all substances expand when heated.

30. Would a bimetallic strip function if the two different metals have the same rates of expansion? Is it important that they expand at different rates? Explain.

31. Steel plates are commonly attached to each other with rivets, which are slipped into holes in the plates and rounded over with hammers. The hotness of the rivets makes them easier to round over, but their hotness has another important advantage in providing a tight fit. What is it?

32. An old method for breaking boulders was to put them in a hot fire and then to douse them with cold water. Why would this fracture the boulders?

33. After you have driven a car for some distance, why does the air pressure in the tires increase?

34. Structural groaning noises are sometimes heard in the attic of old buildings on cold nights. Give an explanation in terms of thermal expansion.

35. An old remedy for a pair of nested drinking glasses that stick together is to run water at different temperatures into the inner glass and over the surface of the outer glass. Which water should be hot, and which cold?

36. Why is it important that glass mirrors used in astronomical observatories be composed of glass with a low "coefficient of expansion"?

37. In terms of thermal expansion, why is it important that a key and its lock be made of the same or similar materials?

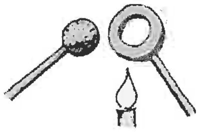
38. Any architect will tell you that chimneys are never used as a weight-bearing part of a wall. Why?

39. Looking at the expansion joint in the photo of Figure 15.13, would you say it was taken on a warm day or a cold day? Why?

40. Would you or the gas company gain by having gas warmed before it passed through your gas meter?

41. After filling your gas tank to the top and parking your car in direct hot sunlight, why does the gasoline overflow?

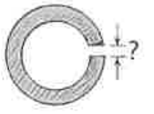
42. A metal ball is just able to pass through a metal ring. When Anette increases the temperature of the ball, however, it will not pass through the ring. What would happen if she instead increased the temperature of the ring, rather than the ball? Will the size of the hole increase, stay the same, or decrease?



43. Consider a pair of brass balls of the same diameter, one hollow and the other solid. Both are heated with equal increases in temperature. Compare the diameters of the heated balls.

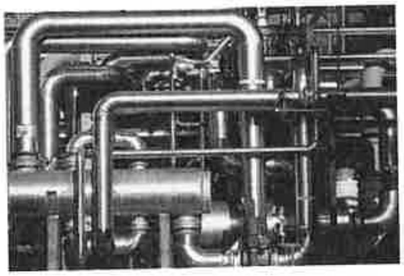
44. After a machinist very quickly slips a hot, snugly fitting iron ring over a very cold brass cylinder, there is no way that the two can be separated intact. Can you explain why this is so?

45. Suppose that you cut a small gap in a metal ring. If you were to heat the ring, would the gap become wider or narrower?



46. When a mercury thermometer is warmed, the mercury level momentarily goes down before it rises. Can you give an explanation for this?

47. Why do long steam pipes often have one or more relatively large U-shaped sections of pipe?



48. Why are incandescent bulbs typically made of very thin glass?

49. One of the reasons the first lightbulbs were expensive was due to the platinum electrical lead wires into the bulb, necessary because they expanded at about the same rate as glass when heated. Why is it important that the metal leads and the glass have the same coefficient of expansion?

50. After you measure the dimensions of a plot of land with a steel tape on a hot day, you return and remeasure the same plot on a cold day. On which day do you determine the larger area for the land?

51. What was the precise temperature at the bottom of Lake Superior at 12:01 AM on October 31, 2000?

52. Suppose that water is used in a thermometer instead of mercury. If the temperature is at 4°C and then changes, why can't the thermometer indicate whether the temperature is rising or falling?

53. A piece of solid iron sinks in a container of molten iron. A piece of solid aluminum sinks in a container of molten aluminum. Why does a piece of solid water (ice) not sink in a container of "molten" (liquid) water? Explain, using molecular terms.

54. How would the shape of the 0°C–18°C curve in Figure 15.20 differ if density rather than volume were plotted against temperature? Make a rough sketch.

55. What happens to the volume of water as it is cooled from 3°C to 1°C?

56. How does the combined volume of the billions and billions of hexagonal open spaces in the structures of ice crystals in a piece of ice compare with the portion of ice that floats above the waterline?

57. State whether water at the following temperatures will expand or contract when warmed a little: 0°C; 4°C; 6°C.

58. Why is it important to protect water pipes in the winter so that they don't freeze?

59. If water had a lower specific heat capacity, would ponds be more likely to freeze or less likely to freeze?

60. If cooling occurred at the bottom of a pond instead of at the surface, would the pond freeze from the bottom up? Explain.

PROBLEMS

1. What would be the final temperature of a mixture of 50 g of 20°C water and 50 g of 40°C water?

2. Suppose that a brass rod 1.0 m long expands 0.5 cm when its temperature is increased a certain amount. By how much will a brass rod 100 m long expand with the same change of temperature?

3. Steel expands 11 parts in a million for each 1°C change. Think about the 1.3-km main span of steel for the Golden Gate Bridge. If the span had no expansion joints, show that the span would be 0.21 m longer for a 15°C increase in temperature. [Use the formula $\Delta L = \alpha L_0 \Delta T$, where L_0 is the original length, α is the "coefficient of expansion" that for steel is (1/1,000,000) per °C, and ΔT is the change in temperature.]

• **4.** Consider a 40,000-km steel pipe that forms a ring to fit snugly all around the circumference of the Earth. Suppose people along its length breathe on it so as to raise its temperature 1°C. The pipe gets longer. It also is no longer snug. How high does it stand above ground level? (To simplify, consider only the expansion of its radial distance from the center of Earth, and apply the geometry formula that relates circumference C and radius r, $C = 2\pi r$. The result is surprising!)

CHAPTER 15 ONLINE RESOURCES

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Videos

- Low Temperatures with Liquid Nitrogen
- How a Thermostat Works

Quizzes

Flashcards

Links

16 Heat Transfer

1 Rocket scientist Helen Yan, when she was my student in the 1980s, showing how a hole in the box looks perfectly black and indicates a black interior. 2 The snow-covered mailboxes raise a question: What physics explains why the light-colored ones are snow covered, while the black ones are free of snow? 3 More recent photos of Helen who shows the same box—yes, with a white interior.

When Helen Yan was the top-scoring student in my physics class back in 1984, and then became my teaching assistant, I half-seriously suggested she continue in physics and become a rocket scientist. She may have taken me seriously, for after getting both a B.S. and M.S. in physics, today she *is* a rocket scientist. Back then she posed for the above pair of photos at the left, which first appeared in the fifth edition of *Conceptual Physics,* when all physics books were printed in only black ink. Color didn't occur in this book until the seventh edition. Helen then posed again for the same pair of photos in full color, and these photos have continued in editions since then.

In the pair of photos she is illustrating a property of radiation and, interestingly, today she specializes in radiation in the infrared part of the spectrum. Her science career began when she monitored the details of rocket launches with Lockheed Martin. Presently, in addition to teaching physics part-time at City College of San Francisco, and ballroom/swing dancing, she is involved in the designs of imaging sensors that are carried in satellites for viewing details of Earth's surface.

Helen is a personal merit badge in my teaching career, and a role model for others. So when you encounter a bright girl or young woman unsure of a career objective, suggest she follow Helen's path and, yes, even become a rocket scientist!

Conduction

Suppose you're roasting marshmallows on the end of a long metal fork over a campfire. While waiting to toast a crunchy surface on the marshmallow, the fork becomes a bit hot to hold. Heat enters the fork at the end that is kept in the flames and is transmitted along the entire length to your hand. The transmission of heat in this manner is called **conduction.** The fire causes the atoms at the heated end of the fork to move more rapidly. These atoms vibrate against neighboring atoms, which, in turn, do the same. More important, free electrons that can drift through the metal are made to jostle and transfer energy by colliding with atoms and other free electrons within the material.

fyi

- The spontaneous transfer of heat is always from warmer objects to cooler objects and is brought about in three ways: by *conduction,* by *convection,* and by *radiation.*

How well a metal fork or any solid object conducts heat depends on the bonding within its atomic or molecular structure. Solids built of atoms that have one or more "loose" outer electrons conduct heat (and electricity) well. Metals have the "loosest" outer electrons, which are free to carry energy by collisions throughout the metal. That is why metals are excellent conductors of heat and electricity. Silver is the best conductor, copper is next, and, among the common metals, aluminum and then iron are next in order. Wool, wood, straw, paper, cork, and Styrofoam, on the other hand, are poor conductors of heat. The outer electrons in the atoms of these materials are firmly attached. Poor conductors are called *insulators.*

FIGURE 16.1

When you touch a nail stuck in ice, does cold flow from the nail to your hand, or does energy flow from your hand to the nail?

Because wood is a good insulator (poor conductor) of heat, it is used for handles of cookware. Even when it is hot, you can grasp the wooden handle of a pot with your bare hand and quickly remove the pot from a hot stove without harm. Grasping an iron handle of the same temperature would surely burn your hand. Wood is a good insulator even when very hot, which is why firewalkers can walk barefoot on red-hot wooden coals without burning their feet. (CAUTION: Don't try this on your own; even experienced firewalkers sometimes receive bad burns when conditions aren't just right—bits of coals sticking to the feet, for example.) The principal factor in firewalking is the low conductivity of wood—even red-hot wood. Although its temperature is high, relatively little heat is conducted to the feet, just as little heat is conducted by air when you put your hand briefly in a hot pizza oven. If you touch metal in the hot oven—OUCH! Similarly, a firewalker who steps on a hot piece of metal or another good conductor will be burned. Evaporation of moisture on wet feet can play a role in firewalking too, as we'll see in the next chapter.

PhysicsPlace.com™
Video
The Secret to Walking on Hot Coals

Most liquids and gases are poor conductors of heat. Air is a very poor conductor, which is why your hand isn't harmed if placed briefly in a hot oven. The good insulating properties of such things as wool, fur, and feathers are largely due to the air spaces they contain. Other porous substances such as fiberglass are likewise good insulators because of their many small air spaces. Be glad that air is a poor conductor; if it weren't, you'd feel quite chilly on a 20°C (68°F) day!

The feeling of warmth or cold for different materials involves rates of heat transfer, not necessarily temperatures.

Snow is a poor conductor (a good insulator)—about the same as dry wood. Hence, a blanket of snow can literally keep the ground warm in winter. Snowflakes are formed of crystals, which collect into feathery masses, imprisoning air and thereby interfering with the escape of heat from Earth's surface. Traditional Arctic winter dwellings are shielded from the cold by their snow covering. Animals in the forest find shelter from the cold in snowbanks and in holes in the snow. The snow doesn't provide warmth; it simply slows down the loss of the heat that the animals generate.

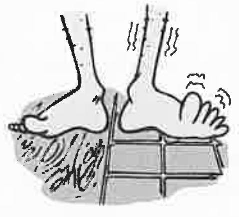

FIGURE 16.2

The tile floor feels colder than the wooden floor, even though both floor materials are at the same temperature. This is because tile is a better conductor of heat than wood, and so heat is more readily conducted out of the foot touching the tile.

Heat is transmitted from a higher to a lower temperature. We often hear people say that they wish to keep the cold out of their homes. A better way to state this is to say that they want to prevent the heat from escaping. There is no "cold" that flows into a warm home (unless a cold wind blows into it). A home becomes colder

FIGURE 16.3

Snow patterns on the roof of a house show areas of conduction and insulation. Bare parts show where heat from inside has leaked through the roof and melted the snow.

because heat flows out. Homes are insulated with rock wool to prevent heat loss rather than to prevent cold from entering. It is important to note that no insulator can totally prevent heat loss. An insulator merely reduces the rate at which heat penetrates. In winter, even the best-insulated warm homes will gradually cool. Insulation slows heat transfer.

PhysicsPlace.com™
Video
Air Is a Poor Conductor

CHECK POINT

1. In desert regions that are hot in the daytime and cold at nighttime, the walls of houses are often made of mud. Why is it important that the mud walls be thick?
2. Why is it that you can place your hand briefly inside a hot oven without harm, but you are burned if you touch the metal sides of the oven?

Check Your Answers

1. A wall of appropriate thickness keeps the house warm at night by slowing the flow of heat from inside to outside, and it keeps the house cool in the daytime by slowing the flow of heat from outside to inside. Such a wall has "thermal inertia."
2. When your hand is in the air of the hot oven, you're not harmed mainly because air is a poor conductor—heat doesn't travel well between the hot air and your hand. Touching the hot metal sides of the oven is another story, for metal is an excellent conductor and considerable heat flows into your hand.

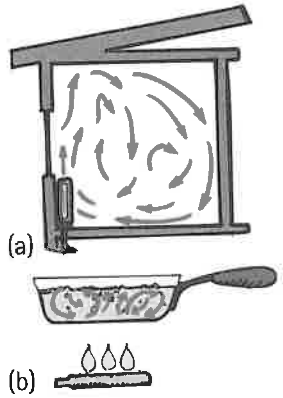

FIGURE 16.4

(a) Convection currents in air.
(b) Convection currents in liquid.

Convection

Liquids and gases transmit heat mainly by **convection,** which is heat transfer due to the actual motion of the fluid itself. Unlike conduction (in which heat is transferred by successive collisions of electrons and atoms), convection involves the motion of "blobs" of matter—the overall movement of molecules of a fluid.

Convection can occur in all fluids, whether liquids or gases. Whether we heat water in a pan or heat air in a room, the process is the same (Figure 16.4). As the fluid is heated from below, the molecules at the bottom begin moving faster, spreading apart more, becoming less dense, and are buoyed upward. Denser, cooler fluid moves in to take the place of the warmer fluid at the bottom. In this way, convection currents keep the fluid stirred up as it heats—warmer fluid moving away from the heat source and cooler fluid moving toward the heat source.

Convection currents occur in the atmosphere and affect the weather. When air is warmed, it expands. In expanding, it becomes less dense than the surrounding air. Like a balloon, it is buoyed upward. When the rising air reaches an altitude at which its density matches that

Convection ovens are simply ovens with a fan inside, which speeds up cooking by the circulation of warmed air.

FIGURE 16.5

A heater at the tip of a J-tube submerged in water produces convection currents, which are revealed as shadows (caused by deflections of light in water of different temperatures).

of the surrounding air, it no longer rises. This is evident when we see smoke from a fire rise and then level off as it cools to match the density of the surrounding air. Rising warm air expands as it rises because less atmospheric pressure squeezes it at higher altitudes. As the air expands, it cools. (Do the following experiment right now. With your mouth open, blow on your hand. Your breath is warm. Now repeat, but this time pucker your lips to make a small hole so your breath expands as it leaves your mouth. Note that your breath is appreciably cooler! Expanding air cools.) This is the opposite of what occurs when air is compressed. If you've ever compressed air with a tire pump, you probably noticed that both air and pump become quite hot.

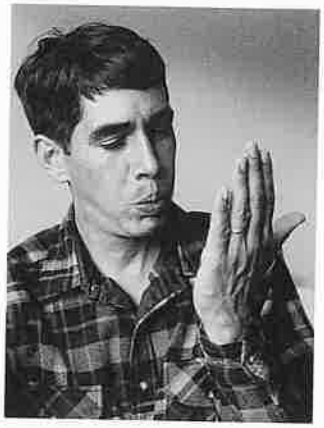

FIGURE 16.6

Blow warm air onto your hand from your wide-open mouth. Now reduce the opening between your lips so that the air expands as you blow. Do you notice a difference in air temperature?

We can understand the cooling of expanding air by thinking of molecules of air as tiny Ping-Pong balls bouncing against one another. A ball picks up speed when it is hit by another that approaches with a greater speed. But when a ball collides with one that is receding, its rebound speed is reduced. Likewise for a Ping-Pong ball moving toward a paddle: It picks up speed when it hits an approaching paddle, but it loses speed when it hits a receding paddle. The same idea applies to a region of air that is expanding: Molecules collide, on average, with more molecules that are receding than with molecules that are approaching (Figure 16.7). Thus, in expanding air, the average speed of the molecules decreases and the air cools.[1]

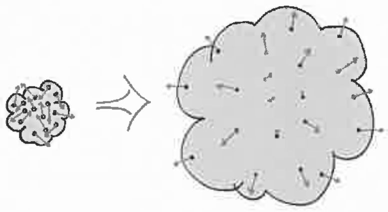

FIGURE 16.7

Molecules in a region of expanding air collide more often with receding molecules than with approaching ones. Their rebound speeds therefore tend to decrease and, as a result, the expanding air cools.

A dramatic example of cooling by expansion occurs with steam expanding through the nozzle of a pressure cooker (Figure 16.8). The cooling effect of both expansion and rapid mixing with cooler air allows you to hold your hand comfortably in the jet of condensed vapor. (*Caution:* If you try this, be sure to place your hand high above the nozzle at first and then lower it to a comfortable distance. If you put your hand at the nozzle where no steam appears, watch out! Steam is invisible near the nozzle before it has sufficiently expanded and cooled. The cloud of "steam" that you see is actually condensed water vapor, which is much cooler.)

FIGURE 16.8

The hot steam expands from the pressure cooker and is cool to Millie's touch.

Convection currents stirring the atmosphere result in winds. Some parts of Earth's surface absorb heat from the Sun more readily than others, and, as a result, the air near the surface is heated unevenly and convection currents form. This is evident at the seashore. In the daytime, the shore warms more easily than the water; air over the shore is pushed up (we say it rises) by cooler air that comes in from above the water to take its place. The result is a sea breeze. At night, the process reverses, because the shore cools off more quickly than the water, and then the warmer air is over the sea (Figure 16.9). If you build a fire on the beach, you'll notice that the smoke sweeps landward during the day and seaward at night.

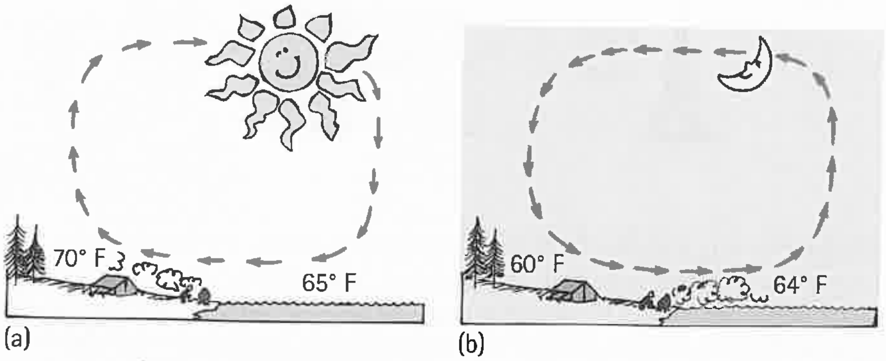

FIGURE 16.9

Convection currents produced by unequal heating of land and water. (a) During the day, warm air above the land rises, and cooler air over the water moves to replace it. (b) At night, the direction of air flow is reversed because then the water is warmer than the land.

---

[1] Where does the energy go in this case? We will see, in Chapter 18, that it goes into work done on the surrounding air as the expanding air pushes outward.

Convection occurs wherever fluids are subjected to temperature differences. It produces clouds in the sky and contributes to oceanic currents in deep ocean waters. In Earth's interior, the convection of semimolten material is the likely cause of sliding tectonic plates, which produce events such as earthquakes and volcanic eruptions. Convection plays a large role in the Sun. Convection is a central player in much that occurs around us.

CHECK POINT

You can hold your fingers beside the candle flame without harm, but not above the flame. Why?

Check Your Answer

Hot air travels upward by air convection. Since air is a poor conductor, very little heat travels sideways to your fingers.

Radiation

Energy from the Sun passes through space and then through Earth's atmosphere and warms Earth's surface. This energy does not pass through the atmosphere by conduction, because air is a poor conductor. Nor does it pass through by convection, for convection begins only after Earth is warmed. We also know that neither convection nor conduction is possible in the empty space between our atmosphere and the Sun. We can see that energy must be transmitted by some other means—by **radiation.**[2] The energy so radiated is called *radiant energy.*

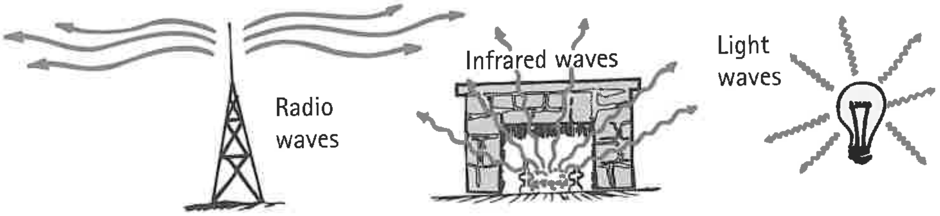

FIGURE 16.10
Types of radiant energy (electromagnetic waves).

Radiant energy is in the form of *electromagnetic waves.* It includes radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. These types of radiant energy are listed in order of wavelength, from longest to shortest. Infrared (below-the-red) radiation has longer wavelengths than visible light. The longest visible wavelengths are for red light, and the shortest are for violet light. Ultraviolet (beyond-the-violet) radiation has shorter wavelengths. (Wavelength is treated in more detail in Chapter 19, and electromagnetic waves are covered in more detail in Chapters 25 and 26.)

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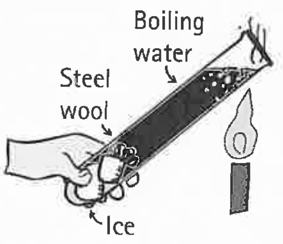
[2] The radiation we are talking about here is electromagnetic radiation, including visible light. Don't confuse this with radioactivity, a process of the atomic nucleus that we'll discuss in Part 7.

Practicing Physics

Hold the bottom end of a test tube full of cold water in your hand. Heat the top part in a flame until the water boils. The fact that you can still hold the bottom of the test tube shows that glass and water are poor conductors of heat and that convection does not move the hot water downward. This is even more dramatic when you wedge chunks of ice at the bottom with some steel wool; then the water above can be brought to a boil without melting the ice. Try it and see.



The wavelength of radiation is related to the *frequency* of radiation. Frequency is the rate of vibration of a wave. The girl in Figure 16.11 shakes a rope at a low frequency (left) and at a higher frequency (right). Note that the low-frequency shake produces a long, lazy wave and the higher-frequency one produces shorter waves. Likewise with electromagnetic waves. We will see, in Chapter 26, that vibrating electrons emit electromagnetic waves. Low-frequency vibrations produce long waves and high-frequency vibrations produce shorter waves.

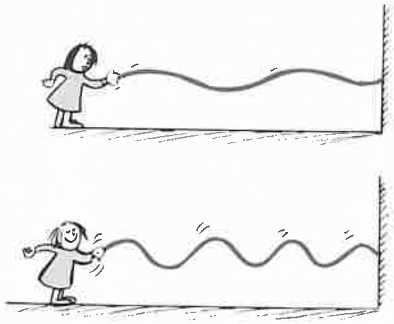


FIGURE 16.11

A wave of long wavelength is produced when the rope is shaken gently (at a low frequency). When it is shaken more vigorously (at a high frequency), a wave of shorter wavelength is produced.

EMISSION OF RADIANT ENERGY

All substances at any temperature above absolute zero emit radiant energy. The peak frequency $\bar{f}$ of the radiant energy is directly proportional to the absolute (Kelvin) temperature T of the emitter (Figure 16.12):

$$\bar{f} \sim T$$

If an object is hot enough, some of the radiant energy it emits is in the range of visible light. At a temperature of about 500°C an object begins to emit the longest waves we can see, red light. Higher temperatures produce a yellowish light. At about 1500°C all the different waves to which the eye is sensitive are emitted and we see an object as "white-hot." A blue-hot star is hotter than a white-hot star, and a red-hot star is less hot. Since a blue-hot star has twice the light frequency of a red-hot star, it therefore has twice the surface temperature of a red-hot star.[3]

Radiation by Earth is *terrestrial radiation.* Radiation by the Sun is *solar radiation.* Both are regions in the electromagnetic spectrum. (What do you call radiation from that special someone?)

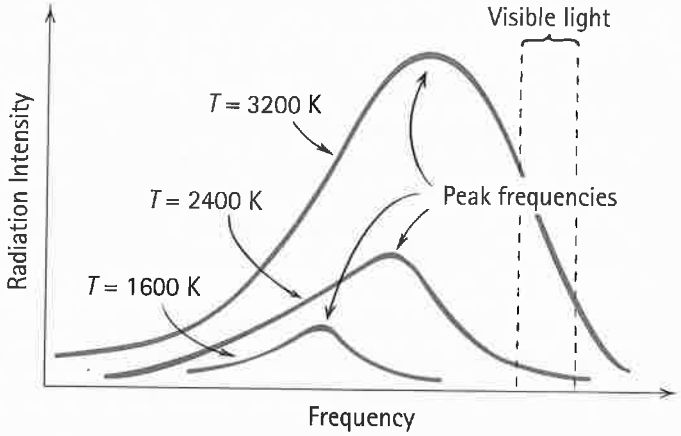


FIGURE 16.12

INTERACTIVE FIGURE

Radiation curves for different temperatures. The peak frequency of radiant energy is directly proportional to the absolute temperature of the emitter.

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[3] The *amount* of radiant energy Q emitted by an object is proportional to the fourth power of the Kelvin temperature, $Q \sim T^4$.

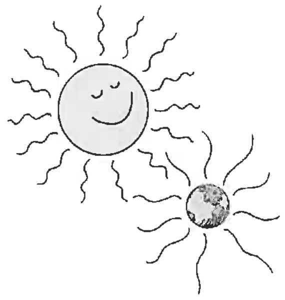

FIGURE 16.13

Both the Sun and Earth emit the same kind of radiant energy. The Sun's glow is visible to the eye; Earth's glow consists of longer waves and isn't visible to the eye.

Because the surface of the Sun has a high temperature (by earthly standards), it therefore emits radiant energy at a high frequency—much of it in the visible portion of the *electromagnetic spectrum.* The surface of Earth, by comparison, is relatively cool, and so the radiant energy it emits has a frequency lower than that of visible light. The radiation emitted by Earth is in the form of *infrared waves*—below our threshold of sight. Radiant energy emitted by Earth is called **terrestrial radiation.**

The Sun's radiant energy stems from nuclear reactions in its deep interior. Likewise, nuclear reactions in Earth's interior warm Earth (visit the depths of any mine and you'll find it's warm down there—year-round). Much of this internal energy conducts to the surface to become terrestrial radiation.

All objects—you, your instructor, and everything in your surroundings—continually emit radiant energy over a range of frequencies. Objects with everyday temperatures emit mostly low-frequency infrared waves. When the higher-frequency infrared waves are absorbed by your skin, as when standing beside a hot stove, you feel the sensation of heat. So it is common to refer to infrared radiation as *heat radiation.* Common infrared sources that give the sensation of heat are the Sun, a lamp filament, and burning embers in a fireplace.

Heat radiation underlies infrared thermometers. You simply point the thermometer at something whose temperature you want, press a button, and a digital temperature reading appears. The radiation emitted by the object in question provides the reading. Typical classroom infrared thermometers operate in the range of about −30°C to 200°C.

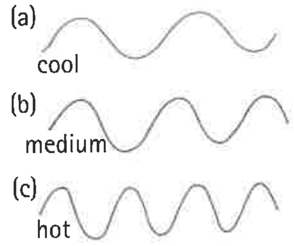

FIGURE 16.14

(a) A low-temperature (cool) source emits primarily low-frequency, long-wavelength waves. (b) A medium-temperature source emits primarily medium-frequency, medium-wavelength waves. (c) A high-temperature (hot) source emits primarily high-frequency, short-wavelength waves.

CHECK POINT

Do any of the following *not* give off radiant energy? (a) The Sun. (b) Lava from a volcano. (c) Red-hot coals. (d) This book that you're reading.

Check Your Answer

Let's hope you didn't answer (d), the book. Why? Because the book, like the other substances listed, has temperature—though not as much. According to the rule $\bar{f} \sim T$, it therefore emits radiation whose peak frequency $\bar{f}$ is quite low compared with the radiation frequencies emitted by the other substances. Everything with any temperature above absolute zero emits electromagnetic radiation. That's right—*everything!*

FIGURE 16.15

An infrared thermometer measures the infrared radiant energy emitted by a body and converts it to temperature.

ABSORPTION OF RADIANT ENERGY

If everything is emitting energy, why doesn't everything finally run out of it? The answer is that everything is also absorbing energy. Good emitters of radiant energy are also good absorbers; poor emitters are poor absorbers. For example, a radio antenna constructed to be a good emitter of radio waves is also, by its very design, a good receiver (absorber) of them. A poorly designed transmitting antenna is also a poor receiver.

The surface of any material, hot or cold, both absorbs and emits radiant energy. If the surface absorbs more energy than it emits, it is a net absorber and its temperature rises. If it emits more than it absorbs, it is a net emitter and its temperature drops. Whether a surface plays the role of net emitter or net absorber depends on whether its temperature is above or below that of its surroundings. If the surface is hotter than its surroundings, it will be a net emitter and will cool. If its surface is colder than its surroundings, it will be a net absorber and become warmer. Every surface, hot or cold, both absorbs and emits radiant energy.

You can verify this with a pair of metal containers of the same size and shape, one having a white or mirrorlike surface and the other having a blackened surface

(Figure 16.16). Fill the containers with hot water and place a thermometer in each. You will find that the black container cools faster. The blackened surface is a better emitter. Coffee or tea stays hot longer in a shiny pot than in a blackened one. The same experiment can be done in reverse. This time, fill each container with ice water and place the containers in front of a fireplace, outside on a sunny day, or wherever there is a good source of radiant energy. You'll find that the black container warms up faster. As said, an object that emits well also absorbs well.

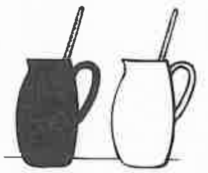

FIGURE 16.16

When the containers are filled with hot (or cold) water, the blackened one cools (or warms) faster.

CHECK POINT

1. If a good absorber of radiant energy were a poor emitter, how would its temperature compare with the temperature of its surroundings?
2. A farmer turns on the propane burner in his barn on a cold morning and heats the air to 20°C (68°F). Why does he still feel cold?

Check Your Answers

1. If a good absorber were not also a good emitter, there would be a net absorption of radiant energy and the temperature of the absorber would remain higher than the temperature of the surroundings. Things around us approach a common temperature only because good absorbers are, by their very nature, also good emitters.
2. The walls of the barn are still cold. The farmer radiates more energy to the walls than the walls radiate back, and he is chilled. (Inside your home or your classroom, you are comfortable only if the walls are warm, not just the air.)

Emission and absorption in the visible part of the spectrum are affected by color, whereas the infrared part of the spectrum is more affected by surface texture. A dull finish emits/absorbs better in the infrared than a polished one, whatever its color.

REFLECTION OF RADIANT ENERGY

Absorption and reflection are opposite processes. A good absorber of radiant energy reflects very little radiant energy, including visible light. Hence, a surface that reflects very little or no radiant energy looks dark. So a good absorber appears dark and a perfect absorber reflects no radiant energy and appears completely black. The pupil of the eye, for example, allows light to enter with no reflection, which is why it appears black. (An exception occurs in flash photography when pupils appear red, which occurs when very bright light is reflected off the eye's inner red surface and back through the pupil.)

Look at the open ends of pipes in a stack; the holes appear black. Look at open doorways or windows of distant houses in the daytime, and they, too, look black. Openings appear black because the light that enters them is reflected back and forth on the inside walls many times and is partly absorbed at each reflection. As a result, very little or none of the light remains to come back out of the opening and travel to your eyes (Figure 16.17). Helen Yan nicely illustrates this in the chapter-opening photos.

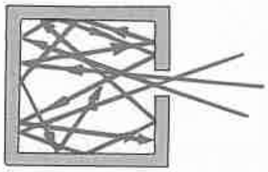

FIGURE 16.17

Radiation that enters the cavity has little chance of exiting because most of it is absorbed. For this reason, the opening to any cavity looks black to us.

A hot pizza placed outside on a winter day is a net emitter. The same pizza placed in a hotter oven is a net absorber.

Good reflectors, on the other hand, are poor absorbers. Clean snow is a good reflector and therefore does not melt rapidly in sunlight. If the snow is dirty, it absorbs radiant energy from the Sun and melts faster. Dropping black soot from an aircraft onto snow-covered mountains is a technique sometimes used in flood control. Controlled melting at favorable times, rather than a sudden runoff of melted snow, is thereby accomplished.

FIGURE 16.18

Most of the heat provided by a heating radiator is accomplished by convection, so color makes little difference (a better name for this type of heater would be a *convector*). For optimum efficiency, however, a silver-painted radiator will radiate less, become and remain hotter, and do a better job of heating the air. So paint your radiator silver!

COOLING AT NIGHT BY RADIATION

Bodies that radiate more energy than they receive become cooler. This happens at night when solar radiation is absent. An object left out in the open at night radiates energy into

FIGURE 16.19

Patches of frost crystals betray the hidden entrances to mouse burrows. Each cluster of crystals is frozen mouse breath!

space and, because of the absence of any warmer bodies in the vicinity, receives very little energy from space in return. Thus, it gives out more energy than it receives and becomes cooler. But if the object is a good conductor of heat—such as metal, stone, or concrete—heat conducts to the ground, which somewhat stabilizes its temperature. On the other hand, materials such as wood, straw, and grass are poor conductors and little heat is conducted into them from the ground. These insulating materials are net radiators and get *colder than the air.* It is common for frost to form on these kinds of materials even when the temperature of the air does not go down to freezing. Have you ever seen a frost-covered lawn or field on a chilly but above-freezing morning before the Sun is up? The next time you see this, notice that the frost forms only on the grass, straw, or other poor conductors, while none forms on the cement, stone, or other good conductors.

Serious gardeners will cover their favorite plants with a tarp when they expect a frost. The plants radiate just as before, but now they are receiving radiant energy from the tarp rather than from the dark night sky. Because the tarp radiates as an object at the temperature of the surroundings rather than at the temperature of the cold, dark sky, frost doesn't form on the plants' leaves. This is the same reason that plants on a covered porch won't have frost on them, whereas plants exposed to the open sky will.

Earth itself exchanges radiation with its surroundings. The Sun is a dominant part of Earth's surroundings during the day. The sunlit half of Earth absorbs more radiant energy than it emits. At night, if the air is relatively transparent, Earth radiates more energy to deep space than it receives in return. As the Bell Laboratories researchers Arno Penzias and Robert Wilson learned in 1965, outer space has a temperature—about 2.7 K (2.7 degrees above absolute zero). Space itself emits weak radiation characteristic of that low temperature.[4]

fyi

- In any given hour, more energy from the Sun reaches Earth than the entire energy used from all sources by the whole human population in any given year.

CHECK POINT

1. Which is likely to be colder—a night when you can see the stars or a night when you cannot?
2. In winter, why does the road surface on a bridge tend to be more icy than the road surfaces at either end of the bridge?

Check Your Answers

1. It is colder on the starry night, when Earth's surface radiates directly to frigid deep space. On a cloudy night, net radiation is less, because the clouds radiate energy back to Earth's surface.
2. Energy radiated by roads on land is partly replenished by heat conducted from the warmer ground below the pavement. But there's an absence of thermal contact between the road surfaces of bridges and the ground, so they receive very little, if any, replenishing energy conducted from the ground. This is why road surfaces on bridges get colder than roads on land, which increases the chance of ice formation on bridges. Understanding heat transfer can make you a safer driver!

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[4] Penzias and Wilson shared a Nobel Prize for this discovery of "cosmic background radiation," deemed to be a relic of the Big Bang. Its temperature has now been measured to the incredible accuracy of 2.725 K, and it is revealing much about the early history of the universe and its present composition.

Newton's Law of Cooling

Left to themselves, objects hotter than their surroundings eventually cool to match the surrounding temperature. The rate of cooling depends on how much hotter the object is than its surroundings. A hot apple pie will cool more each minute if it is put in a cold freezer than if it is left on the kitchen table. That's because, in the freezer, the temperature difference between the pie and its surroundings is greater. Similarly, the rate at which a warm house leaks internal energy to the cold outdoors depends on the difference between the inside and outside temperatures.

The rate of cooling of an object—whether by conduction, by convection, or by radiation—is approximately proportional to the temperature difference ΔT between the object and its surroundings.

$$\text{Rate of cooling} \sim \Delta T$$

This is known as **Newton's law of cooling.** (Guess who is credited with discovering this?) The law applies also to warming. If an object is cooler than its surroundings, its rate of warming up is also proportional to ΔT.[5] Frozen food will warm up faster in a warm room than in a cold room.

The rate of cooling we experience on a cold day can be increased by the added convective effect of the wind. We speak of this in terms of *windchill.* For example, a windchill of −20°C means we are losing heat at the same rate as if the temperature were −20°C without wind.

FIGURE 16.20

The long stem of a wine glass helps to prevent heat from the hand from warming the wine.

Interestingly, Newton's law of cooling is an empirical relationship, and not a fundamental law like Newton's laws of motion.

CHECK POINT

Since a hot cup of tea loses heat more rapidly than a lukewarm cup of tea, would it be correct to say that a hot cup of tea will cool to room temperature before a lukewarm cup of tea will?

Check Your Answer

No! Although the rate of cooling is greater for the hotter cup, it has farther to cool to reach thermal equilibrium. The extra time is equal to the time it takes to cool to the initial temperature of the lukewarm cup of tea. Cooling *rate* and cooling *time* are not the same thing.

The Greenhouse Effect

An automobile parked in the street in the bright Sun on a hot day with closed windows can get very hot inside—appreciably hotter than the outside air. This is an example of the **greenhouse effect,** so named for the same temperature-raising effect in florists' glass greenhouses. Understanding the greenhouse effect requires knowing about two concepts.

The first concept has been previously stated—that all things radiate, and the frequency and wavelength of radiation depend on the temperature of the object emitting the radiation. High-temperature objects radiate short waves; low-temperature

A significant role of glass in a florist's greenhouse is preventing convection of cooler outside air with warmer inside air. So the greenhouse effect actually plays a bigger role in global warming than it does in the warming of florists' greenhouses.

---

[5] A warm object that contains a source of energy may remain warmer than its surroundings indefinitely. The internal energy it emits doesn't necessarily cool it, and Newton's law of cooling doesn't apply. Thus an automobile engine that is running remains warmer than the automobile's body and the surrounding air. But after the engine is turned off, it cools in accordance with Newton's law of cooling and gradually approaches the same temperature as its surroundings. Likewise, the Sun will remain hotter than its surroundings as long as its nuclear furnace is functioning—another 5 billion years or so.

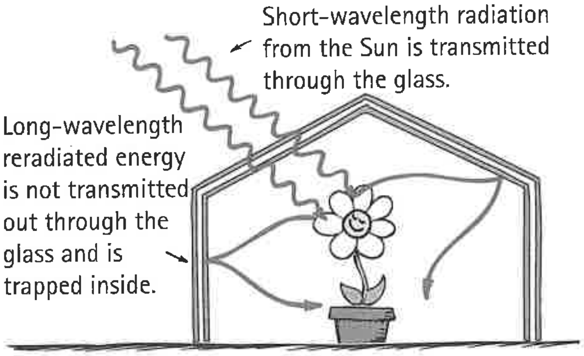

FIGURE 16.21

Glass is transparent to short-wavelength radiation but opaque to long-wavelength radiation. Reradiated energy from the plant is of long wavelength because the plant has a relatively low temperature.

objects radiate long waves. The second concept we need to know is that the transparency of things such as air and glass depends on the wavelength of radiation. Air is transparent to both infrared (long) waves and visible (short) waves, unless the air contains excess water vapor and carbon dioxide, in which case it is opaque to infrared. Glass is transparent to visible light waves, but is opaque to infrared waves. (The physics of transparency and opacity is discussed in Chapter 26.)

Now to why that car gets so hot in bright sunlight: Compared with the car, the Sun's temperature is very high. This means the waves radiated by the Sun are very short. These short waves easily pass through both Earth's atmosphere and the glass windows of the car. So energy from the Sun gets into the car interior, where, except for reflection, it is absorbed. The interior of the car warms up. The car interior radiates its own waves, but, since it is not as hot as the Sun, the waves are longer. The reradiated long waves encounter glass that isn't transparent to them. So the reradiated energy remains in the car, which makes the car's interior even warmer (which is why leaving your pet in a car on a hot sunny day is a no-no).

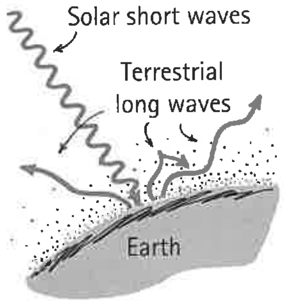

FIGURE 16.22

INTERACTIVE FIGURE

The hot Sun emits short waves, and the cool Earth emits long waves. Water vapor, carbon dioxide, and other "greenhouse gases" in the atmosphere retain heat that would otherwise be radiated from Earth to space.

The same effect occurs in Earth's atmosphere, which is transparent to solar radiation. The surface of Earth absorbs this energy and reradiates part of this as longer-wavelength terrestrial radiation. Atmospheric gases (mainly water vapor and carbon dioxide) absorb and re-emit much of this long-wavelength terrestrial radiation back to Earth. Terrestrial radiation that cannot escape Earth's atmosphere keeps Earth from getting too cold. This greenhouse effect is very nice, for Earth would be a frigid −18°C otherwise. Over the last 500,000 years the average temperature of Earth has fluctuated between 19°C and 27°C and is presently at the high point, 27°C—and climbing.

Although H_2O is the major greenhouse gas in the atmosphere, the second most abundant greenhouse gas, CO_2, is notorious because its contribution from humans has been steadily increasing. Unhappily, further warming by CO_2 can trigger more H_2O as well. So our present environmental concern is the combination of growing amounts of both these molecules in the atmosphere, which would further increase the temperature and produce a new thermal balance unfavorable to the biosphere.

An important credo is "You can never change only one thing." Change one thing, and you change another. A slightly higher Earth temperature means slightly warmer oceans, which means changes in weather and storm patterns. The consensus among scientists is that Earth's climate is getting too warm too fast. This phenomenon is called *global warming.* How this will play out is not known. At one extreme, corrections can be made and life will be fine for Earth's inhabitants. At the other extreme, we are reminded of the planet Venus, which in earlier times may have had a climate somewhat similar to Earth's. A runaway greenhouse effect is thought to have occurred on Venus, which today finds its atmosphere 96% carbon dioxide, with an average surface temperature of 460°C. Venus is the hottest planet in the solar system. We certainly don't want to follow its course. Our fate likely lies between these extremes. We don't know.

Volcanoes put more particulate matter into the atmosphere, by far, than industries and all human activity.

What we do know is that energy consumption and modifying our atmosphere is related to population size. We are seriously questioning the idea of continued growth. (Please take the time to read Appendix E, "Exponential Growth and Doubling Time"—very important material.)

Solar power is what you have once solar energy has been converted to electricity. This can be done by photovoltaic cells or by changing water to steam to spin a generator.

CHECK POINT

1. What eventually happens to the solar energy that falls on Earth?
2. What does it mean to say that the greenhouse effect is like a one-way valve?

Check Your Answers

1. Sooner or later, it will be radiated back into space. Energy is always in transit—you can rent it, but you can't own it.
2. The transparent material—atmosphere for Earth and glass for the greenhouse—allows only incoming short waves and blocks outgoing long waves. As a result, radiant energy is trapped within the "greenhouse."

Solar Power

If you step from the shade into the sunshine, you're noticeably warmed. The warmth you feel isn't so much because the Sun is hot, for its surface temperature of 6000°C is no hotter than the flames of some welding torches. We are warmed principally because the Sun is so *big*.[6] As a result, it emits enormous amounts of energy, less than one part in a billion of which reaches Earth. Nonetheless, the amount of radiant energy received each second over each square meter at right angles to the Sun's rays at the top of the atmosphere is 1400 joules (1.4 kJ). This input of energy is called the **solar constant.** This is equivalent, in power units, to 1.4 kilowatts per square meter (1.4 kW/m^2). **Solar power** is the rate at which solar energy is received from the Sun. The amount of solar power that reaches the ground is attenuated by the atmosphere and reduced by nonperpendicular elevation angles of the Sun. Also, of course, it ceases at night. The solar power received in the United States, averaged over day and night, summer and winter, is about 13% of the solar constant (0.18 kW/m^2). This amount of power, illuminating the roof of a typical American house, is twice the power needed to comfortably heat and cool the house year-round. More and more homes are capturing solar energy for space heating and water heating. Also gaining in popularity are photovoltaic shingles used in roofing buildings.

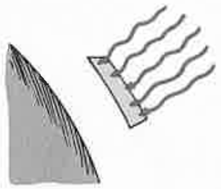

FIGURE 16.23

Over each square meter of area perpendicular to the Sun's rays at the top of the atmosphere, the Sun pours 1400 J of radiant energy each second. Hence the solar constant is 1.4 kJ/s/m^2, or 1.4 kW/m^2.

Photovoltaic systems convert light energy directly to electrical energy. They can be designed for power needs ranging from milliwatts to megawatts, powering a calculator or a generator in a power plant. They also can be located in remote areas not readily accessible to utility grid lines. Solar-energy collecting and concentration systems, whether arrays of mirrors or photovoltaic cells, are becoming competitive in cost with electrical power generated by conventional power sources.

FIGURE 16.25

A simple and effective use of solar power.

FIGURE 16.24

Higher-tech solar water heaters are covered with glass to provide a greenhouse effect, which further heats the water. Why are the collectors a dark color?

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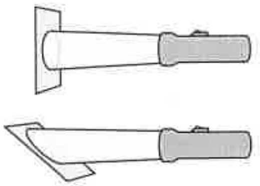
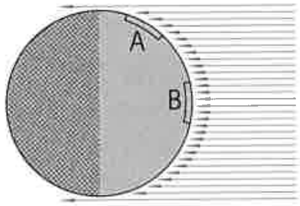
[6] To visualize how big the Sun is, realize that its diameter is more than 3 times the distance between Earth and the Moon. So if Earth and the Moon were inside the Sun, with Earth at the solar center, the Moon would be deep inside. The Sun is *really* big!

Practicing Physics



Does the distance from the Sun, or the angle of the Sun's rays on Earth, account for frigid polar regions and tropical equatorial regions? You can see the answer for yourself if you hold a flashlight above a surface and note its brightness. When the light strikes perpendicularly, light energy is concentrated; but, when the surface is tipped, keeping the same distance, incident light is more spread out. Can you see that the same energy over a larger area is akin to the low temperatures of the Arctic and Antarctic regions of Earth?

The sketch to the right is of Earth with parallel rays of light coming from the Sun. Count the number of rays that strike Region A and equal-area Region B. Where is the energy per unit area less? How does this relate to climate?



Controlling Heat Transfer

A nice way to review the methods of heat transfer is by considering a device that inhibits all three methods: the vacuum bottle. A vacuum bottle (known by the trademark name Thermos) consists of a double-walled glass container with a vacuum between the walls and a close-fitting stopper of cork or plastic. (There is usually an outer covering as well.) The glass surfaces that face each other are silvered. Any liquid, hot or cold, in a vacuum bottle will remain close to its original temperature for many hours.

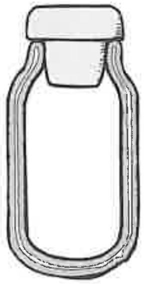


FIGURE 16.26
A Thermos bottle.

1. Heat transfer by *conduction* through the vacuum is impossible. Some heat escapes by conduction through the glass and stopper, but this is a slow process, as glass, plastic, and cork are poor conductors.
2. The vacuum has no fluid to convect, so there is no heat loss through the walls by *convection.*
3. Heat loss by *radiation* is reduced by the silvered surfaces of the walls, which reflect heat waves back into the bottle.

SUMMARY OF TERMS

Conduction The transfer of heat energy by molecular and electron collisions within a substance (especially a solid).

Convection The transfer of heat energy in a gas or liquid by means of currents in the heated fluid. The fluid moves, carrying energy with it.

Radiation The transfer of energy by means of electromagnetic waves.

Terrestrial radiation The radiation emitted by Earth to outer space.

Newton's law of cooling The rate of loss of heat from a warm object is proportional to the temperature difference between the object and its surroundings. (Similarly for the gain of heat by a cool object.)

Greenhouse effect Warming of the lower atmosphere by short-wavelength radiation from the Sun that penetrates the atmosphere is absorbed by Earth and is reradiated at longer wavelengths that cannot easily escape Earth's atmosphere.

Solar constant 1400 J/m^2 received from the Sun each second at the top of Earth's atmosphere on an area perpendicular to the Sun's rays; expressed in terms of power, 1.4 kW/m^2.

Solar power Energy per unit time derived from the Sun.

REVIEW QUESTIONS

Conduction

1. What is the role of "loose" electrons in heat conductors?
2. If you touch the metal sides inside of an oven with a bare hand, you're in trouble. But hold your hand briefly in the oven air and you're okay. What does this tell you about the relative conductivities of metal and air?
3. Explain why a firewalker can step quickly without harm on red-hot coals with bare feet.

4. Why are such materials as wood, fur, feathers, and even snow good insulators?
5. Does a good insulator prevent heat from escaping, or does it simply slow its passage?

Convection

6. What happens to the volume of air as it rises? What happens to its temperature?
7. When an air molecule is hit by an approaching faster-moving molecule, does its rebound speed increase or decrease? How about when it hits a receding molecule?
8. How are the speeds of molecules of air affected when the air is compressed by the action of a tire pump?
9. How are the speeds of molecules of air affected when the air rapidly expands?
10. Why is Millie's hand not burned when she holds it above the escape valve of the pressure cooker (Figure 16.8)?
11. Why does the direction of coastal winds change from day to night?

Radiation

12. In what form does radiant energy travel?
13. Relatively speaking, do high-frequency waves have long wavelengths or short wavelengths?

Emission of Radiant Energy

14. How does the frequency of radiant energy relate to the absolute temperature of the radiating source?
15. What is terrestrial radiation?
16. Cite a primary difference between waves of solar radiation and waves of terrestrial radiation.

Absorption of Radiant Energy

17. Since all objects emit energy to their surroundings, why don't the temperatures of all objects continuously decrease?
18. What determines whether an object is a net absorber or a net emitter of radiant energy at a given time?
19. Which will normally warm faster—a black pot of cold water or a silvered pot of cold water? Explain.

Reflection of Radiant Energy

20. Can an object be both a good absorber and a good reflector at the same time? Why, or why not?
21. Why does the pupil of the eye appear black?

Cooling at Night by Radiation

22. What happens to the temperature of something that radiates energy without absorbing the same amount in return?
23. An object radiating energy at night is in contact with the relatively warm Earth. How does its conductivity affect whether or not it becomes appreciably colder than the air?

Newton's Law of Cooling

24. Which will undergo the greater rate of cooling—a red-hot poker in a warm oven or a red-hot poker in a cold room (or do both cool at the same rate)?
25. Does Newton's law of cooling apply to warming as well as to cooling?

The Greenhouse Effect

26. What would be the consequence of completely eliminating the greenhouse effect?
27. In what way does glass act like a one-way valve for a conventional greenhouse? Does the atmosphere play the same role?

Solar Power

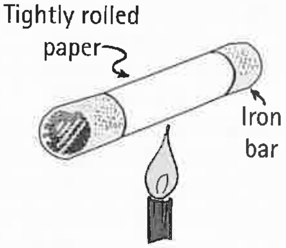
28. How much radiant energy from the Sun, on average, reaches each square meter at the top of Earth's atmosphere each second?
29. What is the function of a photovoltaic cell?

Controlling Heat Transfer

30. Cite three ways in which a Thermos bottle inhibits heat transfer.

PROJECTS

1. Wrap a piece of paper around a thick metal bar and place it in a flame. Notice that the paper will not catch fire. Can you explain this in terms of the conductivity of the metal bar? (Paper generally will not ignite until its temperature reaches about 230°C.)



2. Turn a common incandescent lamp on and off quickly while holding your hand a few inches from the bulb. You feel its heat, but, when you touch the bulb, it isn't hot. Explain this in terms of radiant energy and the bulb's transparency.
3. Write a letter to Grandma and share your knowledge about why air temperature is cooler on clear nights and warmer on cloudy nights. With reasoned examples, convince her that all things are continually emitting energy—and absorbing energy.

EXERCISES

1. On a cold day, why does a metal doorknob feel colder than the wooden door?
2. What is the explanation for feather beds being warm?
3. Wrap a fur coat around a thermometer. Will the temperature rise?
4. If 70°F air feels warm and comfortable to us, why does 70°F water feel cool when we swim in it?

5. At what common temperature will a block of wood and a block of metal both feel neither hot nor cold to the touch?
6. If you hold one end of a piece of metal against a piece of ice, the end in your hand soon becomes cold. Does cold flow from the ice to your hand? Explain.
7. What is the purpose of a layer of copper or aluminum on the bottom of stainless steel cookware?
8. In terms of physics, why do restaurants serve baked potatoes wrapped in aluminum foil?
9. Wood is a better insulator than glass, yet fiberglass is commonly used as an insulator in wooden buildings. Explain.
10. Many tongues have been injured by licking a piece of metal on a very cold day. Why would no harm result if a clean piece of wood were licked on the same day?
11. Visit a snow-covered cemetery and note that the snow does not slope upward against the gravestones. Instead, it forms depressions, as shown. Can you think of a reason for this?

12. Why are mittens warmer than gloves on a cold day?
13. If you were caught in freezing weather with only your own body heat as a source, would you be warmer in an Arctic igloo or in a wooden shack? Defend your answer.
14. Wood conducts heat very poorly—it has a very low conductivity. Does wood still have a low conductivity if it is hot? Could you quickly and safely grasp the wooden handle of a pan from a hot oven with your bare hand? Although the pan handle is hot, is much heat conducted from it to your hand if grasped briefly? Why would it be a poor idea to do the same with an iron handle? Explain.
15. Does wood have a low conductivity if it is very hot—that is, in the stage of smoldering, red-hot coals? Could you safely walk across a bed of red-hot wooden coals with bare feet? Although the coals are hot, does much heat conduct from them to your feet if you step quickly? Could you do the same on red-hot iron coals? Explain. (*Caution:* Coals can stick to your feet, so—OUCH!—don't try it!)
16. Is it possible for heat to flow between two objects with the same internal energy? Can heat flow from an object with less internal energy to one with more internal energy? Defend your answers.
17. When two cups of hot chocolate, one at 50°C and the other at 60°C, are poured into a bowl, why will the temperature of the mixture be between 50°C and 60°C?
18. Why is it incorrect to say that, when a hot object warms a cold object, temperature flows between them?
19. Why is it incorrect to say that, when a hot object warms a cold one, the increase in temperature of the cold one is equal to the decrease in temperature of the hot one? When is this statement correct?
20. A friend says that the molecules in a mixture of gas in thermal equilibrium have the same average kinetic energy. Do you agree or disagree? Explain.
21. Your friend states that the average speed of all hydrogen and nitrogen molecules in a gas is the same. Do you agree or disagree, and why?
22. Why would you not expect all the molecules of air in your room to have the same average speed?
23. In a mixture of hydrogen and oxygen gases at the same temperature, which molecules move faster? Why?
24. One container is filled with argon gas and the other with krypton gas. If both gases have the same temperature, in which container are the atoms moving faster? Why?
25. Which atoms, on average, move slower in a mixture, U-238 or U-235? How would this affect diffusion through a porous membrane of otherwise identical gases made from these isotopes?
26. Solid uranium can be converted chemically to uranium fluoride, UF_6, which can be cooked up into a dense vapor that diffuses through a porous barrier. Which is likely to diffuse at a greater rate, a gas with isotope U-235 or U-238?
27. Consider two equal-size rooms connected by an open door. One room is maintained at a higher temperature than the other one. Which room contains more air molecules?
28. In a still room, smoke from a candle will sometimes rise only so far, not reaching the ceiling. Explain why.
29. Soaring birds and glider pilots can remain aloft for hours without expending power. How do they do it?
30. Why does helium, released into the atmosphere, eventually disappear into space?
31. Ice cubes float in a glass of iced tea. Why would cooling be less if the cubes were instead on the bottom of the drink?
32. Release a single molecule in an evacuated region and it will fall as fast as, and no differently from, a baseball released in the same region. Explain.
33. Air density is normally less above any point in air than below, providing a "migration window" in air. How does this affect the movement of faster-moving molecules in air?
34. What does the high specific heat of water have to do with convection currents in the air at the seashore?
35. If we warm a volume of air, it expands. Does it then follow that if we expand a volume of air, it warms? Explain.
36. Ceiling fans can make you feel cooler in a warm room. Do ceiling fans reduce room temperature?
37. Some ceiling fans are reversible so that they drive air down or pull it up. In which direction should the fan drive the air during winter? In which direction for summer?
38. A snow-making machine used for ski areas blows a mixture of compressed air and water through a nozzle. The temperature of the mixture may initially be well above the freezing temperature of water, yet crystals of snow are formed as the mixture is ejected from the nozzle. Explain how this happens.
39. In which form of heat transfer is a medium not required?
40. Why does a good *emitter* of heat radiation appear black at room temperature?
41. Since energy is radiated by all objects, why can't we see them in the dark?
42. A number of bodies at different temperatures placed in a closed room share radiant energy and ultimately reach a common temperature. Would this thermal equilibrium be possible if good absorbers were poor emitters and poor absorbers were good emitters? Explain.
43. From the rules that a good absorber of radiation is a good radiator and a good reflector is a poor absorber, state a rule relating the reflecting and radiating properties of a surface.
44. The heat of volcanoes and natural hot springs comes from trace amounts of radioactive minerals in common rock in Earth's interior. Why isn't the same kind of rock at Earth's surface warm to the touch?

45. Even though metal is a good conductor, frost can be seen on parked cars in the early morning even when the air temperature is above freezing. Provide an explanation.
46. When there is morning frost on the grass in an open park, why is frost unlikely to be found on the ground directly beneath park benches?
47. Why is whitewash sometimes applied to the glass of florists' greenhouses in the summer?
48. On a very cold sunny day, you wear a black coat and a transparent plastic coat. Which coat should be worn on the outside for maximum warmth?
49. If the composition of the upper atmosphere were changed so that it permitted a greater amount of terrestrial radiation to escape, what effect would this have on Earth's climate?
50. Is it important to convert temperatures to the Kelvin scale when we use Newton's law of cooling? Why or why not?
51. Why is the insulation in an attic commonly thicker than the insulation in the walls of a house?
52. Suppose that, at a restaurant, you are served coffee before you are ready to drink it. In order that it be hottest when you are ready for it, should you add cream to the coffee right away or wait until you are ready to drink it?
53. If you wish to save fuel and you're going to leave your warm house for a half hour or so on a very cold day, should you turn your thermostat down a few degrees, turn it off altogether, or let it remain at the room temperature you desire?
54. If you wish to save fuel and you're going to leave your cool house for a half hour or so on a very hot day, should you turn your air-conditioning thermostat up a bit, turn it off altogether, or let it remain at the room temperature you desire?
55. As more energy from fossil fuels and other fuels is released on Earth, the overall temperature of Earth tends to rise. How does temperature equilibrium explain why Earth's temperature cannot rise indefinitely?
56. Make up a multiple-choice question that would test a classmate's understanding of the distinction between conduction and convection. Make another in which the term *radiation* is the correct answer.

PROBLEMS

1. In lab, Will burns a 0.6-g peanut beneath 50 g of water, which increases in temperature from 22°C to 50°C. The amount of heat absorbed by the water can be found with the equation $Q = cm\Delta T$, where Q is the amount of heat, c the specific heat of water, m the mass of water, and ΔT the change in the water's temperature.
   a. Assuming that 40% of the heat released makes its way to the water, show that the food value of the peanut is 3500 calories, or 3.5 Calories.
   b. What is the food value in calories per gram? In Calories per gram?
2. Radioactive decay of granite and other rocks in Earth's interior provides sufficient energy to keep the interior molten, to heat lava, and to provide warmth to natural hot springs. This is due to the average release of about 0.03 J per kilogram each year. Show that a 500°C increase in temperature for a thermally insulated chunk of granite takes about 13.3 million years. (Assume that the specific heat capacity c of granite is 800 J/kg·C°. Use the equation $Q = cm\Delta T$.)
3. In a 25°C room, hot coffee in a vacuum flask cools from 75°C to 50°C in 8 hours. Explain why you predict that its temperature after another 8 hours will be 37.5°C.
4. At a certain location, the solar power per unit area reaching Earth's surface is 200 W/m^2, averaged over a 24-hour day. If the average power requirement in your home is 3 kW and you can convert solar power to electric power with 10% efficiency, how large a collector area will you need to meet all your household energy requirements from solar energy? (Will a collector fit in your yard or on your roof?)

• 5. In lab you submerge 100 g of 40°C iron nails in 100 g of 20°C water (the specific heat of iron is 0.12 cal/g°C.) (a) Equate the heat gained by the water to the heat lost by the nails and show that the final temperature of the water becomes 22.1°C. (b) Your lab partner is surprised by the result and says that since the masses of iron and water are equal, the final water temperature should lie closer to 30°C, half-way between. What is your explanation?

CHAPTER 16 ONLINE RESOURCES

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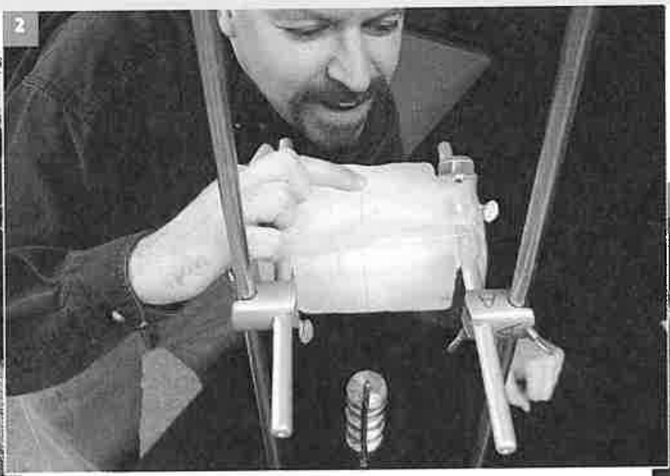
17 Change of Phase



1 Nephew John Suchocki walks barefoot without harm on hot coals (stepping quickly!). 2 Dean Baird demonstrates regelation, illustrated later in Figure 17.15. 3 Ron Hipschman at the Exploratorium removes a piece of ice from the Water Freezer exhibit. When room-temperature water was placed in the chamber and a vacuum was drawn, rapid evaporation cooled the water to ice, as we shall investigate in Figure 17.13.

A good measure of physics teacher effectiveness is the percentage of students in the school who take a course in physics. When Dean Baird began his teaching career at Rio Americano High School in Sacramento, California, in 1986, some 10% of graduates had taken a physics course. Today that percentage is more than 70%, with physics as an elective. Of the students who take Dean's Advanced Placement Physics courses, over 90% earn a passing grade of 3 or higher on the AP test. In addition to coaching science teams at his school, mentoring statewide workshops for new physics teachers, and advising the California State Board of Education regarding statewide science exams, he is the author of my physics and physical science laboratory manuals. A glance at his web site, www.phyz.org, indicates how busy a teacher can be! He is also an accomplished photographer. Dean has been recognized at the local, state, and national levels for outstanding service in physics education and was honored with its 2008 Distinguished Service Citation award by the American Association of Physics Teachers. Dean's specialties as a teacher are curricular diversity and skepticism. He mixes labs, demos, presentations, web video, and active assessment with critical thinking lessons to keep students engaged every day.

Dean loves thermal physics. He plays with hot and cold with a gusto his students love him for. He can't make snowballs in Sacramento, but in lab he can demonstrate regelation, as shown above. He shows how the metal wire slowly passes through the block of ice, refreezing as it goes, so that the ice remains intact. This chapter is about phases of matter and the changes in energy that occur whenever a change of phase occurs.

Phases of Matter

Matter around us exists in four common *phases* (or *states*). Ice, for example, is the *solid* phase of H_2O. Add energy, and you add motion to the rigid molecular structure, which breaks down to form H_2O in the *liquid* phase, water. Add more energy, and the liquid changes to the *gaseous* phase. Add still more energy, and the molecules break into ions and electrons, giving the *plasma* phase. The phase of matter depends on its temperature and the pressure that is exerted on it. Changes of phase almost always require a transfer of energy.

When water turns to a gas, we call it water vapor.

Evaporation

Water in an open pan will eventually evaporate, or dry up. The liquid that disappears becomes water vapor in the air. **Evaporation** is a change of phase from liquid to gas that occurs at the surface of a liquid.

The temperature of any substance is related to the average kinetic energy of its particles. Molecules in liquid water have a wide variety of speeds, moving about in all directions and bumping against one another. At any moment, some move at very high speeds while others barely move at all. In the next moment, the slowest molecule may become the fastest due to molecular collisions. Some gain kinetic energy while others lose kinetic energy. Molecules at the surface that gain kinetic energy by being bumped from below may have enough energy to break free from the liquid. They can leave the surface and escape into the space above the liquid. In this way, they become molecules of vapor.

The increased kinetic energy of molecules bumped hard enough to break free from the liquid comes from molecules remaining in the liquid. This is "billiard-ball physics": When balls bump into one another and some gain kinetic energy, others lose the same amount of kinetic energy. Molecules about to be propelled out of the liquid are the gainers, while the losers of energy remain in the liquid. Thus the average kinetic energy of the molecules remaining in the liquid is lowered—evaporation is a cooling process. Interestingly, the fast molecules that break free from the surface are slowed as they fly away due to their attraction to the surface. So although the water is cooled by evaporation, the air above is not correspondingly warmed by the process.

Nearly 90% of Earth's atmospheric moisture comes from evaporation of its oceans, lakes, and rivers. The rest comes from plant transpiration.

FIGURE 17.1

When wet, the cloth covering on the sides of the canteen promotes cooling.

The canteen shown in Figure 17.1 keeps cool because of evaporation when the cloth that covers the sides is kept wet. As the faster-moving water molecules break free from the cloth, the temperature of the cloth decreases. The cool wet cloth, in turn, cools the metal canteen by conduction, which, in turn, cools the water inside. So energy is transferred from the water in the canteen to the air outside. In this way, the water is cooled appreciably below the air temperature outside.

The cooling effect of evaporation is strikingly evident when some alcohol is applied to your body. The alcohol evaporates very rapidly, cooling the surface of the body quickly. The more rapid the evaporation, the faster the cooling.

When our bodies overheat, our sweat glands produce perspiration. This is part of nature's thermostat, for the evaporation of perspiration cools us and helps us to maintain a stable body temperature. Many animals have very few sweat glands or none at all and must cool themselves by other means (Figures 17.2 and 17.3).

FIGURE 17.2

Like other dogs, Tammy's dogs have no sweat glands (except between their toes). They cool by panting. In this way, evaporation occurs in the mouth and within the bronchial tract.

FIGURE 17.3

Pigs, having no sweat glands, wallow in the mud to cool themselves.

The rate of evaporation is greater at higher temperatures because there is a greater proportion of molecules having sufficient kinetic energy to escape the liquid. Water evaporates at lower temperatures, too, but at a lower rate. A puddle of water, for example, may slowly evaporate to dryness on a cool day.

Even frozen water "evaporates." This form of evaporation, in which molecules are bumped directly from a solid (ice or snow) to a gaseous phase bypassing the liquid phase, is called **sublimation.** Because water molecules are so tightly held in the solid phase, frozen water does not evaporate (sublime) as readily as liquid water. Sublimation, however, does account for the loss of significant portions of snow and ice, and it is especially high on sunny days in dry climates.

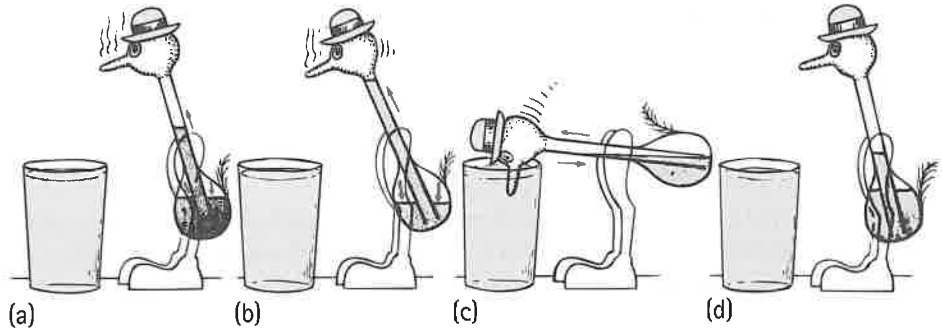


FIGURE 17.4

The toy drinking bird operates by the evaporation of ether inside its body and by the evaporation of water from the outer surface of its head. The lower body contains liquid ether, which evaporates rapidly at room temperature. As it (a) vaporizes, it (b) increases pressure (inside arrows), which pushes ether up the tube. Ether in the upper part does not vaporize because the head is cooled by the evaporation of water from the outer felt-covered beak and head. When the weight of ether in the head is sufficient, the bird (c) pivots forward, permitting the ether to flow back to the body. Each pivot wets the felt surface of the beak and head, and (d) the cycle is repeated.

CHECK POINT

Would evaporation be a cooling process if molecules of every speed had an equal chance to escape from the liquid surface?

Check Your Answer

No. If molecules of all speeds escaped equally easily from the surface, the molecules left behind would have the same range of speeds as before any escaped, and there would be no change of the liquid's temperature. When only the faster molecules can break free, those remaining are slower, and the liquid becomes cooler.

Condensation

The opposite of evaporation is **condensation**—the changing of a gas to a liquid. When gas molecules near the surface of a liquid are attracted to the liquid, they strike the surface with increased kinetic energy and become part of the liquid. In collisions with low-energy molecules in the liquid, excess kinetic energy is shared with the liquid, increasing the liquid temperature. Condensation is a warming process.

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Video
Condensation Is a Warming Process

A dramatic example of the warming that results from condensation is the energy released by steam when it condenses—a painful experience if it condenses on you. That's why a steam burn is much more damaging than a burn from boiling water of the same temperature; the steam releases considerable energy when it condenses to a liquid and wets the skin. This energy release by condensation is utilized in steam-heating systems.

Steam is water vapor at a high temperature, usually 100°C or more. Cooler water vapor also releases energy when it condenses. In taking a shower, for example, you're warmed by condensation of vapor in the shower region—even vapor from a cold shower—if you remain in the moist shower area. You quickly sense the difference if you step outside. Away from the moisture, net evaporation takes place quickly and you feel chilly. But, if you remain in the shower stall, even with the water turned off, the warming effect of condensation counteracts the cooling effect of evaporation. If as much moisture condenses as evaporates, you feel no change in body temperature. If condensation exceeds evaporation, you are warmed. If evaporation exceeds condensation, you are cooled. So now you know why you can dry yourself with a towel much more comfortably if you remain in the shower stall. To dry yourself thoroughly, you can finish the job in a less moist area.

FIGURE 17.5

Internal energy is released by steam when it condenses inside the "radiator."

Spend a July afternoon in dry Tucson or Phoenix where evaporation is appreciably greater than condensation. The result of this pronounced evaporation is a much cooler feeling than you would experience in a same-temperature July afternoon in New York City or New Orleans. In these humid locations, condensation noticeably counteracts evaporation, and you feel the warming effect as vapor in the air condenses on your skin. You are literally being bombarded by the impact of H_2O molecules in the air slamming into you. Put more mildly, you are warmed by the condensation of vapor in the air upon your skin.

FIGURE 17.6

If you're chilly outside the shower stall, step back inside and be warmed by the condensation of the excess water vapor.

CHECK POINT

If the water level in a dish of water remains unchanged from one day to the next, can you conclude that no evaporation or condensation has occurred?

Check Your Answer

Not at all, for there is much activity taking place at the molecular level. Both evaporation and condensation occur continuously. The constant water level simply indicates equal rates of both, not that nothing's happening. When just as many molecules evaporate as condense, no *net* evaporation or condensation occurs. The two processes cancel each other.

CONDENSATION IN THE ATMOSPHERE

There is always some water vapor in the air. A measure of the amount of this water vapor is called *humidity* (mass of water per volume of air). Weather reports often use the term *relative humidity*—the ratio of the amount of water vapor currently in the air at a given temperature to the largest amount of water vapor the air can contain at that temperature.[1]

Air that contains as much vapor as it can is saturated. Saturation occurs when the air temperature drops and water-vapor molecules in the air begin condensing. Water molecules tend to stick together. Because of their normally high average speeds in air, however, most water molecules do not stick together when they collide. Instead, these fast-moving molecules bounce back when they collide and therefore remain in the

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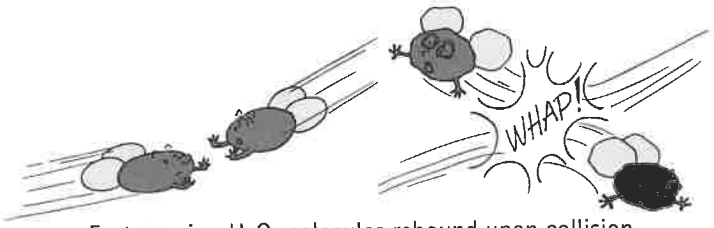
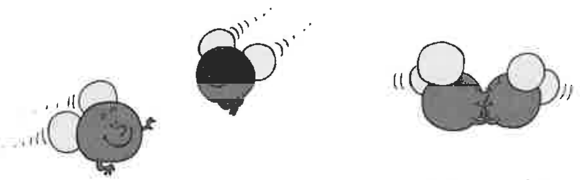
[1] Relative humidity is a good indicator of comfort. For most people, conditions are ideal when the temperature is about 20°C and the relative humidity is between 50% and 60%. When the relative humidity is higher, moist air feels "muggy" as condensation counteracts the evaporation of perspiration.



Fast-moving H_2O molecules rebound upon collision



Slow-moving H_2O molecules coalesce upon collision

FIGURE 17.7
Condensation of water vapor.

fyi

- Does humidity make us feel warmer or colder—or both? If you're already cold, more humidity makes you feel colder. If you're already hot, more humidity makes you feel hotter. At pleasant temperatures, a little humidity makes us more comfortable.

gaseous phase. Some water molecules move more slowly than average, though, and these slow ones are more likely to stick to one another upon collision (Figure 17.7). (This can be understood by thinking of a fly making a grazing contact with sticky flypaper. At a high speed, the fly has enough momentum and energy to rebound from the flypaper into the air without sticking, but at a low speed, it is more likely to get stuck.) So slow-moving water molecules are the ones most likely to condense and to form droplets of water in saturated air. Because lower air temperatures are characterized by slower-moving molecules, saturation and condensation are more likely to occur in cool air than in warm air. Warm air can contain more water vapor than cold air.

CHECK POINT

Why does dew form on the surface of a cold soft-drink can?

Check Your Answer

Water vapor in the warm air is chilled when it makes contact with the cold can. What is the fate of chilled water molecules? They are slower when they collide, and they stick. This is condensation, which is why the surface of a cold can is wet.

FOG AND CLOUDS

Warm air rises. As it rises, it expands. As it expands, it chills. As the air chills, water-vapor molecules too small to be visible are slowed. Lower-speed molecular collisions result in water molecules sticking together. Water molecules combine with tiny particles of dust, salt, and smoke in the air to form cloud droplets that grow and develop into clouds. If these particles are not present, we can stimulate cloud formation by "seeding" the air with appropriate particles or ions.

Warm breezes blow over the ocean and become moist. When the moist air moves from warmer to cooler waters or from warm water to cool land, it chills. As it chills, water-vapor molecules begin sticking rather than bouncing off one another. Condensation takes place near ground level, and we have fog. The difference between fog and a cloud is basically altitude. Fog is a cloud that forms near the ground. Flying through a cloud is much like driving through fog. Check the web for different kinds of fog.

Clouds are normally denser than air. So why don't clouds fall from the sky? The answer is, clouds *do* fall! A stable cloud falls as fast as the upwelling of air beneath it, so it remains stationary. If it falls anyway, we call it fog.

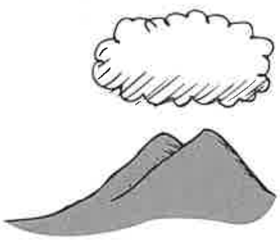


FIGURE 17.8
Why is it common for clouds to form where there are updrafts of warm moist air?

Boiling

Under the right conditions, evaporation can take place beneath the surface of a liquid, forming bubbles of vapor that are buoyed to the surface, where they escape. This change of phase *throughout* a liquid rather than only at the surface is called **boiling.** Bubbles in the liquid can form only when the pressure of the vapor within the bubbles is great enough to resist the pressure of the surrounding liquid. Unless the vapor pressure is great enough, the surrounding pressure will collapse any bubbles that tend to form. At temperatures below the boiling point, the vapor pressure in bubbles is not great enough, so bubbles do not form until the boiling point is reached. At this temperature—100°C for water at atmospheric pressure—molecules are energetic enough to exert a vapor pressure as great as the pressure of the surrounding water (which is due mainly to atmospheric pressure).

It is common to say that we boil water, meaning that we apply heat to it. Actually, the boiling process cools the water.

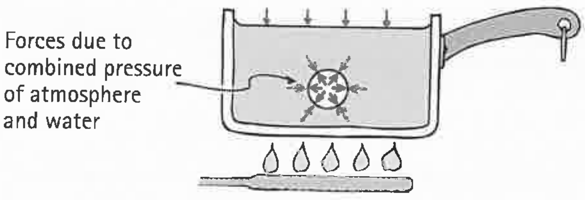


FIGURE 17.9

The motion of water-vapor molecules in the bubble of steam (much enlarged) creates a gas pressure (called the *vapor pressure*) that counteracts the atmospheric and water pressure against the bubble.

If pressure is increased, the molecules in the vapor must move faster to exert enough pressure to keep the bubble from collapsing. Extra pressure can be provided either by going deeper below the surface of the liquid (as in geysers, discussed below) or by increasing the air pressure above the liquid's surface—which is how a pressure cooker works. A pressure cooker has a tight-fitting lid that does not allow vapor to escape until it reaches a certain pressure greater than normal air pressure. As the evaporating vapor builds up inside the sealed pressure cooker, pressure on the surface of the liquid increases, which at first prevents boiling. Bubbles that would normally form are crushed. Continued heating increases the temperature beyond 100°C. Boiling does not occur until the vapor pressure within the bubbles overcomes the increased pressure on the water. The boiling point is raised. Conversely, lowered pressure (as at high altitudes) decreases the boiling point of the liquid. So we see that boiling depends not only on temperature but on pressure as well.

At high altitudes, water boils at a lower temperature. For example, in Denver, Colorado, the Mile-High City, water boils at 95°C instead of at the 100°C boiling temperature characteristic of sea level. If you try to cook food in boiling water of a lower temperature, you must wait a longer time for proper cooking. A 3-minute boiled egg in Denver is yucky. If the temperature of the boiling water is too low, food will not cook at all. It is important to note that it is the high temperature of the water that cooks the food, not the boiling process itself.

FIGURE 17.10

The tight lid of a pressure cooker holds pressurized water vapor above the water's surface, which inhibits boiling. Water therefore boils at a temperature greater than 100°C.

GEYSERS

A geyser is a periodically erupting natural pressure cooker. It consists of a long, narrow, vertical crevice into which underground streams seep (Figure 17.11). The column of water is heated by volcanic heat below to temperatures exceeding 100°C. This can happen because the relatively deep vertical column of water exerts pressure on the deeper water, thereby increasing the boiling point. The narrowness of the shaft shuts off convection currents, which allows the deeper portions to become considerably hotter than the water surface. Water at the surface is less than 100°C, but the water temperature below, where it is being heated, is more than 100°C, high enough to permit boiling before water at the top reaches the boiling point. Boiling therefore begins near the bottom, where the rising bubbles push out the column of water above, and the eruption starts. As the water gushes out, the pressure on the remaining water is reduced. It then boils rapidly and erupts with great force. When the eruption subsides, the crevices fill with new water and the cycle repeats.

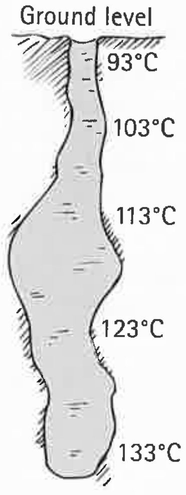


FIGURE 17.11

A geyser of the Old Faithful type.

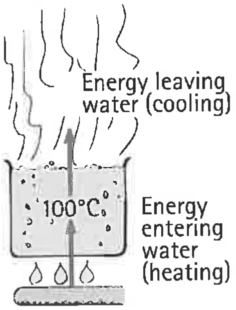


FIGURE 17.12
Heating warms the water, and boiling cools it.

BOILING IS A COOLING PROCESS

Evaporation is a cooling process. So is boiling. At first thought, this may seem surprising—perhaps because we usually associate boiling with heating. But heating water is one thing; boiling is another. When 100°C water at atmospheric pressure is boiling, its temperature remains constant. That means it cools as fast as it warms. By what mechanism? By boiling. If cooling didn't take place, continued input of energy to a pot of boiling water would result in a continued increase in temperature. The reason a pressure cooker reaches higher temperatures is because it prevents normal boiling, which, in effect, prevents cooling.

CHECK POINT

Since boiling is a cooling process, would it be a good idea to cool your hot and sticky hands by dipping them into boiling water?

Check Your Answer

No, no, no! When we say boiling is a cooling process, we mean that the water (not your hands!) is being cooled relative to the higher temperature it would attain otherwise. Because of cooling, it remains at 100°C instead of getting hotter. A dip in 100°C water would be a big ouch!

Mountaineering pioneers in the 19th century, without altimeters, used the boiling point of water to determine their altitudes.

PhysicsPlace.com™
Video
Boiling Is a Cooling Process

BOILING AND FREEZING AT THE SAME TIME

We usually boil water by the application of heat. But we can boil water by the reduction of pressure. We can dramatically show the cooling effect of evaporation and boiling when room-temperature water is placed in a vacuum jar (Figure 17.13). If the pressure in the jar is slowly reduced by a vacuum pump, the water will start to boil. The boiling process removes heat from the water left in the dish, which cools to a lower temperature. As the pressure is further reduced, more and more of the molecules have enough speed to boil away. Continued boiling results in a lowering of temperature until the freezing point of approximately 0°C is reached. Continued cooling by boiling causes ice to form over the surface of the bubbling water. Boiling and freezing are taking place at the same time! This must be witnessed to be appreciated. Frozen bubbles of boiling water are a remarkable sight.[2]

If you spray some drops of coffee into a vacuum chamber, they, too, will boil until they freeze. Even after they are frozen, the water molecules will continue to evaporate into the vacuum until little crystals of coffee solids are left. This is how freeze-dried coffee is made. The low temperature of this process tends to keep the chemical structure of coffee solids from changing. When hot water is added, much of the original flavor of the coffee is restored. Boiling really is a cooling process!

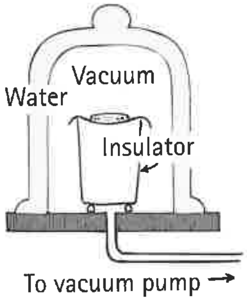


FIGURE 17.13
Apparatus to demonstrate that water will freeze and boil at the same time in a vacuum. A gram or two of water is placed in a dish that is insulated from the base by a polystyrene cup.

PhysicsPlace.com™
Video
Pressure Cooker: Boiling and Freezing at the Same Time

Melting and Freezing

Suppose that you are holding hands with someone, and both of you start jumping around randomly. The more violently you jump, the more difficult holding hands would become. If you were to jump violently enough, holding hands would be impossible. Something like this happens to the molecules of a solid when it is heated. As heat is absorbed, the molecules vibrate more and more violently in a less ordered manner. If enough heat is absorbed, the attractive forces between the molecules will no longer be able to hold them together. The solid melts.

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[2] "Water Freezer" is my favorite exhibit at the Exploratorium in San Francisco. Room-temperature water is placed in a vacuum chamber where it rapidly boils and turns to ice. The exhibit is featured in the opening photograph of this chapter.

Freezing is the reverse of this process. Substances freeze at exactly the same temperature as they melt. As energy is withdrawn from a liquid, molecular motion diminishes until finally the molecules, on the average, are moving slowly enough so that the attractive forces between them are able to cause cohesion. The molecules then vibrate about fixed positions and form a solid.

A pure substance has a definite melting or freezing point at any given pressure. The addition of any impurities will lower this temperature. Hence we can use the freezing or melting point as an indicator of the purity of a substance. For example, at atmospheric pressure, water freezes at 0°C—unless such substances as sugar or salt are dissolved in it. Then the freezing point is lower. In the case of salt in water, chlorine ions grab electrons from the hydrogen atoms in H_2O and impede crystal formation. The result of this interference by "foreign" ions is that slower motion is required for the formation of the six-sided ice-crystal structures. As ice crystals form, the interference is intensified because the proportion of "foreign" molecules or ions among nonfused water molecules increases. Connections become more and more difficult. Only when the water molecules move slowly enough for attractive forces to play an unusually large part in the process can freezing be completed. The ice first formed is almost always pure H_2O.

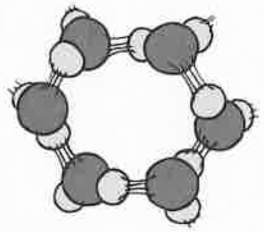

FIGURE 17.14

The open structure of pure ice crystals that normally fuse at 0°C. When impurities are introduced, crystal formation is interrupted, and the freezing temperature is lowered.

REGELATION

Because H_2O molecules form open structures in the solid phase (Figure 17.14), the application of pressure can cause ice to melt. The crystals are simply crushed to the liquid phase. (The temperature of the melting point is only slightly lowered, by 0.007°C for each additional atmosphere of added pressure.) When the pressure is removed, molecules crystallize and refreezing occurs. This phenomenon of melting under pressure and freezing again when the pressure is reduced is called **regelation.** It is one of the properties of water that distinguishes it from other materials.

Regelation is nicely illustrated in Figure 17.15 (and in the opening photo of this chapter). A fine copper wire with weights suspended from its ends is hung over a block of ice.[3] The wire will slowly cut through the ice, but its track will be left full of ice. So the wire and the weights will fall to the floor, leaving the ice a solid block.

Making snowballs is a good example of regelation. When we compress the snow with our hands, we cause a slight melting of the ice crystals; when pressure is removed, refreezing occurs and binds the snow together. Making snowballs is difficult in very cold weather because the pressure we can apply is not enough to melt the snow.

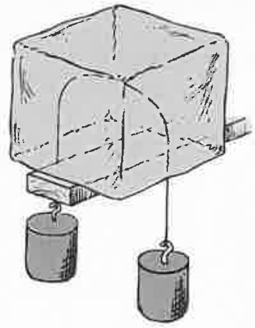

FIGURE 17.15

Regelation. The wire gradually passes through the ice without cutting it in half.

Energy and Changes of Phase

If we continually add heat to a solid or a liquid, the solid or liquid will eventually change phase. A solid will liquefy, and a liquid will vaporize. Energy input is required for both liquefaction of a solid and vaporization of a liquid. Conversely, energy must be extracted from a substance to change its phase in the direction from gas to liquid to solid (Figure 17.16).

The cooling cycle of a refrigerator nicely employs the concepts shown in Figure 17.16. A refrigerator is a **heat pump** that "pumps" heat from a cold environment to a warm one. This is accomplished by a liquid of low boiling point, the refrigerant, which is pumped into the cooling

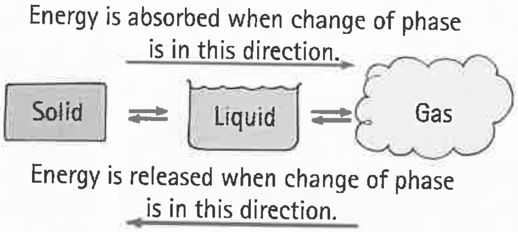

FIGURE 17.16

INTERACTIVE FIGURE

Energy changes with change of phase.

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[3] Changes of phase are occurring as ice melts and the water refreezes. Energy is needed for these changes. When the water immediately above the wire refreezes, it gives up energy. How much? Sufficient to melt an equal amount of ice immediately under the wire. This energy must be conducted through the thickness of the wire. Hence, this demonstration requires that the wire be an excellent conductor of heat. String, for example, won't do.

unit, where it turns into a gas. When changing phase from liquid to gas, heat is drawn from the interior where the food is. The gas, with its added energy, is directed outside to condensation coils. At the coils, heat is released into the outside air as the gas condenses to the liquid phase again. A pump forces the refrigerant through the system, where it is made to undergo cyclic phase changes of vaporization and condensation. The next time you're near a refrigerator, place your hand near the condenser coils in the rear, or at the bottom, and you'll feel the air that has been warmed by the energy extracted from inside.

Heat pumps of various designs are increasingly being utilized to heat (and cool) homes. They typically use less energy than fossil fuel to heat a home. Heat pumps function like a standard refrigerator. Whereas a refrigerator unavoidably warms a room by removing heat from food inside and depositing it at its condensation coils, heat pumps warm a room *deliberately*. Instead of extracting heat from food, they can extract heat from water that is pumped in from nearby underground pipes.[5] Water underground is relatively warm. Subsoil temperatures depend on latitude. In the Midwest and the Central Plains, subsoil temperature below a meter deep is about 13°C (55°F) year-round—warmer than the air in wintertime. Underground pipes outside the home carry 13°C water to a heat pump inside the home. The vaporized refrigerant is then pumped to condensation coils, where it condenses and gives off heat to warm the home. The cooled water is returned to the ground outside, where it warms to ground temperature and repeats the cycle.

A refrigerator is a heat pump. It transfers heat out of a cold environment and into a warm environment. An air conditioner is also a heat pump, with the "cold" environment being indoors and the "warm" environment being outdoors. In both cases, external energy operates the device.

In summer, the process can be reversed, turning the heat pump into a cooler. An air conditioner is itself a heat pump. Employing the same principles, it simply pumps heat energy from the cooler inside of a home to the warmer outside on a summer day. In a crowded city, the effect of thousands of air conditioners operating at once can be to elevate the outdoor temperature somewhat.

So we see that a solid must absorb energy to melt, and a liquid must absorb energy to vaporize. Conversely, a gas must release energy to liquefy, and a liquid must release energy to solidify.

CHECK POINT

When H_2O in the vapor phase condenses, is the surrounding air warmed or cooled?

Check Your Answer

The change of phase is from vapor to liquid, which releases energy (Figure 17.16), so the surrounding air is warmed. Look ahead to Figure 17.7 for another way to see this. Removal of slower molecules from the air raises the average kinetic energy of remaining molecules—hence the warming. This goes hand in hand with water cooling when faster-moving molecules evaporate—where the ones remaining in the liquid phase have a lowered average kinetic energy.

Let's look, in particular, at the changes of phase that occur in H_2O. To make the numbers simple, consider a 1-g piece of ice at a temperature of −50°C in a closed container that is placed on a stove to heat. A thermometer in the container reveals a slow increase in temperature up to 0°C. Then an amazing thing happens. The temperature remains at 0°C even though heat input continues. Rather than getting warmer, the ice begins to melt. In order for the whole gram of ice to melt, 80 calories (335 joules) of energy is absorbed by the ice, not even raising its temperature a

Water's heat of vaporization is huge. The energy needed to vaporize a quantity of boiling water is nearly 7 times the energy needed to melt the same amount of ice.

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[5] Depending on the amount of heat needed, about 200 to 500 meters of piping is normally placed outside the home in trenches about 1.0 to 1.8 meters beneath the ground surface. The configuration of the piping may be horizontal loops or deeper-reaching vertical U-shapes.

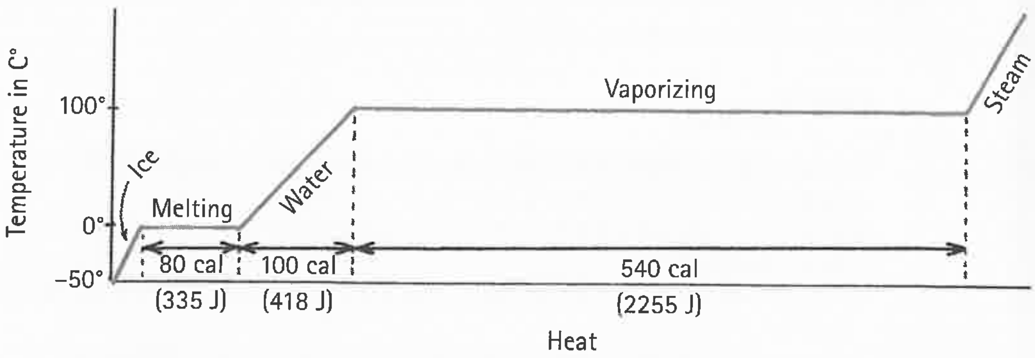

FIGURE 17.17

A graph showing the energy involved in the heating and the changes of phase of 1 g of H_2O.

fraction of a degree. Only when all the ice melts will each additional calorie (4.187 joules) absorbed by the water increase its temperature by 1°C until the boiling temperature, 100°C, is reached. Again, as energy is added, the temperature remains constant while more and more of the gram of water is boiled away and becomes steam. The water must absorb 540 calories (2260 joules) of heat energy to vaporize the whole gram. Finally, when all the water has become steam at 100°C, the temperature begins to rise once more. It will continue to rise as long as energy is added. This process is graphed in Figure 17.17.

Heat of vaporization is either the energy required to separate molecules from the liquid phase or the energy released when gas condenses to the liquid phase.

The 540 calories (2260 joules) required to vaporize a gram of water is a large amount of energy—much more than is required to transform a gram of ice at absolute zero to boiling water at 100°C. Although the molecules in steam and boiling water at 100°C have the same average kinetic energy, steam has more potential energy because the molecules are relatively free of each other and are not bound together as in the liquid phase. Steam contains a vast amount of energy that can be released during condensation.

FIGURE 17.18

On a cold day, hot water may freeze faster than warm water due to the energy that leaves the hot water during rapid evaporation.

So we see that the energies required to melt ice (80 calories, or 335 joules, per gram) and to boil water (540 calories, or 2260 joules, per gram) are the same as the amounts released when the phase changes are in the opposite direction. The processes are reversible. The amount of energy required to change a unit mass of any substance from solid to liquid (and vice versa) is called the **latent heat of fusion** for the substance. (The word *latent* reminds us that this is thermal energy hidden from the thermometer.) For water, we have seen that this is 80 calories per gram (335 joules per gram). The amount of energy required to change any substance from liquid to gas (and vice versa) is called the **latent heat of vaporization** for the substance. For water, this is a whopping 540 calories per gram (2260 joules per gram).[6] It so happens that these relatively high values are due to the strong forces between water molecules—hydrogen bonds.

Heat of fusion is either the energy needed to separate molecules from the solid phase or the energy released when bonds form in a liquid that change it to the solid phase.

The large value of 540 calories per gram for the latent heat of vaporization of water explains why, under some conditions, hot water will freeze faster than warm water.[7] This phenomenon is evident when a thin layer of water is distributed over a large area—like when you wash a car with hot water on a cold winter day or flood a skating rink with hot water, which melts, smoothes out the rough spots, and refreezes quickly. The rate of cooling by rapid evaporation is very high because each evaporating gram of water draws at least 540 calories from the water left behind. This is an enormous amount of energy compared with the 1 calorie per Celsius

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[6] In SI units, the heat of vaporization of water is expressed as 2.260 megajoules per kilogram (MJ/kg), and the heat of fusion of water is 0.335 MJ/kg.

[7] Boiling-hot water will not freeze before cold water does, but it will freeze before moderately hot water does. For example, boiling-hot water will freeze before water warmer than about 60°C, but not before water cooler than 60°C. Try it and see.

FIGURE 17.19

Paul Ryan tests the hotness of molten lead by dragging his wetted finger through it.

FIGURE 17.20

Professor Dave Willey walks barefoot across red-hot wooden coals without harm.

degree that is drawn from each gram of water that cools by thermal conduction. Evaporation is truly a cooling process.

CHECK POINT

1. How much energy is transferred when 1 g of steam at 100°C condenses to water at 100°C?
2. How much energy is transferred when 1 g of boiling water at 100°C cools to ice water at 0°C?
3. How much energy is transferred when 1 g of ice water at 0°C freezes to ice at 0°C?
4. How much energy is transferred when 1 g of steam at 100°C turns to ice at 0°C?

Check Your Answers

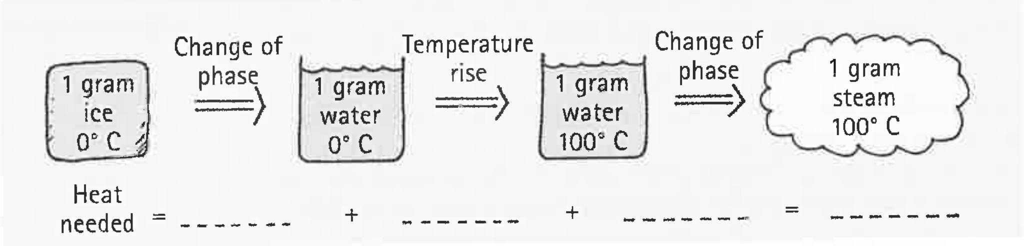
1. One gram of steam at 100°C transfers 540 calories of energy when it condenses to become water at the same temperature.
2. One gram of boiling water transfers 100 calories when it cools 100°C to become ice water.
3. One gram of ice water at 0°C transfers 80 calories to become ice at 0°C.
4. One gram of steam at 100°C transfers to the surroundings a grand total of the above values, 720 calories, to become ice at 0°C.

You dare not touch your dry finger to a hot skillet on a hot stove, but you can certainly do so without harm if you first wet your finger and touch the skillet very briefly. You can even touch it a few times in succession as long as your finger remains wet. This is because energy that ordinarily would go into burning your finger goes instead into changing the phase of the moisture on your finger. The energy converts the moisture to a vapor, which then provides an insulating layer between your finger and the skillet. Similarly, you are able to judge the hotness of a hot clothes iron if you touch it very briefly with a wet finger.

Former supervisor Paul Ryan of the Department of Public Works in Malden, Massachusetts, years ago used molten lead to seal pipes in certain plumbing operations. He startled onlookers by dragging his finger through molten lead to judge its hotness (Figure 17.19). He was sure that the lead was very hot and that his finger was thoroughly wet before doing this. (Do not try this on your own, for if the lead is not hot enough it will stick to your finger and you could be seriously burned!) Similarly, firewalkers walking barefoot on red-hot coals often prefer wet feet (others such as Dave Willey in Figure 17.20 prefer dry feet, claiming hot coals more readily stick to wet feet—OUCH!). The low conductivity of wooden coals, however (as discussed in the previous chapter), is the principal reason the feet of barefoot firewalkers are not burned.

Practicing Physics

Fill in the number of calories or joules at each step in changing the phase of 1 g of 0°C ice to 100°C steam.



CHECK POINT

Suppose that 4 g of boiling water is poured onto a cold surface and that 1 g rapidly evaporates. If evaporation takes 540 calories from the remaining 3 g of water and no other heat transfer takes place, what will be the temperature of the remaining 3 g?

Check Your Answer

The remaining 3 g will turn to 0°C ice. 540 calories from 3 g means each gram gives up 180 calories. 100 calories from a gram of boiling water reduces its temperature to 0°C, and removal of 80 more calories turns it to ice. This is why hot water so quickly turns to ice in a freezing-cold environment. (In practice, because of other heat transfer, more than 1 g of the original 4 g would need to evaporate to freeze the rest.)

SUMMARY OF TERMS

Evaporation The change of phase from liquid to gaseous.

Sublimation The change of phase from solid to gaseous, bypassing the liquid phase.

Condensation The change of phase from gaseous to liquid.

Boiling Rapid evaporation that takes place within a liquid as well as at its surface.

Regelation The process of melting under pressure and the subsequent refreezing when the pressure is removed.

Heat pump A device that transfers heat out of a cool environment and into a warm environment.

Latent heat of fusion The amount of energy required to change a unit mass of a substance from solid to liquid (and released in the reversed process).

Latent heat of vaporization The amount of energy required to change a unit mass of a substance from liquid to gas (and released in the reverse process).

REVIEW QUESTIONS

Phases of Matter

1. What are the four common phases of matter?

Evaporation

2. Do the molecules in a liquid all have about the same speed, or do they have a wide variety of speeds?
3. What is evaporation, and why is it a cooling process? Exactly what is it that cools?
4. Why does warmer water evaporate more readily than cold water?
5. What is sublimation?

Condensation

6. Distinguish between condensation and evaporation.
7. Why is a steam burn more damaging than a burn from boiling water of the same temperature?
8. Why do you feel uncomfortably warm on a hot and humid day?

Condensation in the Atmosphere

9. Distinguish between humidity and relative humidity.
10. Why does water vapor in the air condense when the air is chilled?

Fog and Clouds

11. Why does warm, moist air form clouds when it rises?
12. What is the basic difference between a cloud and fog?

Boiling

13. Distinguish between evaporation and boiling.
14. Does increased atmospheric pressure increase or decrease the boiling point of water? Why is this so?
15. Is it the boiling of water or the higher temperature of water that cooks food faster in a pressure cooker?

Geysers

16. Why will water at the bottom of a geyser not boil when it is at 100°C?
17. What happens to the water pressure at the bottom of a geyser when some of the water above gushes out?

Boiling Is a Cooling Process

18. The temperature of boiling water doesn't increase with continued energy input. Why is this evidence that boiling is a cooling process?

Boiling and Freezing at the Same Time

19. When will water boil at a temperature of less than 100°C?
20. What evidence can you cite for the claim that water can boil at a temperature of 0°C?

Melting and Freezing

21. Why does increasing the temperature of a solid make it melt?
22. Why does decreasing the temperature of a liquid make it freeze?

23. Why does freezing of water not occur at 0°C when foreign ions are present?

Regelation

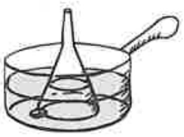
24. What happens to the hexagonal open structure of ice when sufficient pressure is applied to it?
25. Why does a wire not simply cut a block of ice in two when it passes through the ice?

Energy and Changes of Phase

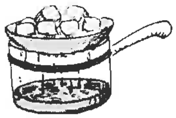
26. Does a liquid release energy or absorb energy when it changes into a gas?
27. Does a liquid release energy or absorb energy when it changes into a solid?
28. Is heat discharged at the back of a refrigerator and by a heat pump given off by vaporization of the refrigerating fluid or by condensation?
29. How many calories are needed to change the temperature of 1 g of water by 1°C? To melt 1 g of ice at 0°C? To vaporize 1 g of boiling water at 100°C?
30. Cite two reasons why firewalkers don't burn their wetted feet when walking barefoot on red-hot coals.

PROJECTS

1. Place a Pyrex funnel mouth-down in a saucepan full of water so that the narrow tube of the funnel protrudes above the water. Rest a part of the funnel on a nail or a coin so that water can get under it. Place the pan on a stove and watch the water as it begins to boil. Where do the bubbles form first? Why? As the bubbles rise, they expand rapidly and push water ahead of them. The funnel confines the water, which is forced up the tube and driven out at the top. Now do you know how a geyser and a coffee percolator work?



2. Watch the spout of a teakettle of boiling water. Notice that you cannot see the steam that issues from the spout. The cloud that you see farther away from the spout is not steam but condensed water droplets. Now hold the flame of a candle in the cloud of condensed steam. Can you explain your observations?
3. You can make rain in your kitchen. Put a cup of water in a Pyrex saucepan or a glass coffeemaker and heat it slowly over a low flame. When the water is warm, place a saucer filled with ice cubes on top of the container. As the water below is heated, droplets form at the bottom of the cold saucer and combine until they are large enough to fall, producing a steady "rainfall" as the water below is gently heated. How does this resemble, and how does it differ from, the way in which natural rain is formed?



4. Measure the temperature of boiling water and the temperature of a boiling solution of salt and water. How do they compare?
5. Do as Dean Baird demonstrates in the chapter-opener photo, or as the sketch shows, and suspend a heavy weight by copper wire over an ice cube. In a matter of minutes, the wire will be pulled through the ice. The ice will melt beneath the wire and refreeze above it, leaving a visible path if the ice is clear.

6. Place a tray of boiling-hot water and a tray of water from a hot-water tap to the same depth in a freezer. See which water will freeze first.
7. Write a letter to Grandma and tell her why bringing water to a boil when she's making tea is actually a process that *cools* the water. Explain how she could convince her teatime friends of this intriguing concept.

EXERCISES

1. Alcohol evaporates more quickly than water at the same temperature. Which produces more cooling—alcohol or the same amount of water on your skin?
2. You can determine wind direction by wetting your finger and holding it up in the air. Explain.
3. When you step out of a swimming pool on a hot, dry day in the Southwest, you feel quite chilly. Why?
4. Why is sweating an efficient mechanism for cooling off on a hot day?
5. Why does blowing over hot soup cool the soup?
6. Can you give two reasons why pouring a cup of hot coffee into a saucer results in faster cooling?
7. What happens to the temperature of a pan of water when evaporation exceeds condensation?
8. What is the source of energy that keeps the dunking bird in Figure 17.4 operating?
9. An inventor claims to have developed a new perfume that lasts a long time because it doesn't evaporate. Comment on this claim.
10. Pretend that all the molecules in a liquid have the same speed, not random speeds. Would evaporation of this liquid cause the remaining liquid to be cooled? Explain.
11. Does a common electric fan cool the air in a room? If not, then why is it used in an overly warm room?
12. Porous canvas bags filled with water are used by travelers in hot weather. When the bags are slung on the outside of a fast-moving car, the water inside is cooled considerably. Explain.
13. Why will wrapping a bottle in a wet cloth at a picnic often produce a cooler bottle than placing the bottle in a bucket of cold water?
14. The human body can maintain its customary temperature of 37°C on a day when the temperature is above 40°C. How is this done?
15. Double-pane windows have nitrogen gas or very dry air between the panes. Why is ordinary air a poor idea?
16. Why are icebergs often surrounded by fog?

17. How does Figure 17.7 help explain the moisture that forms on the inside of car windows when you're parking with your date on a cool night?
18. You know that the windows in your warm house get wet on a cold day. But can moisture form on the windows if the interior of your house is cold on a hot day? How is this different?
19. On freezing days, frost often forms on windows. Why is there usually more frost on the bottom portions of the windows?
20. Why do clouds often form above mountain peaks? (*Hint:* Consider the updrafts.)
21. Why will clouds tend to form above either a flat or a mountainous island in the middle of the ocean? (*Hint:* Compare the specific heat capacity of the land with that of the water and the subsequent convection currents in the air.)
22. A great amount of water vapor changes phase to become water in the clouds that form a thunderstorm. Does this release thermal energy or absorb it?
23. When can you add heat to something without raising its temperature?
24. When can you withdraw heat from something without lowering its temperature?
25. Why does the temperature of boiling water remain the same as long as the heating and boiling continue?
26. Why do vapor bubbles in a pot of boiling water increase in size as they rise in the water?
27. Why does the boiling temperature of water decrease when the water is under reduced pressure, such as when it is at a higher altitude?
28. Place a jar of water on a small stand within a saucepan of water so that the bottom of the jar is held above the bottom of the pan. When the pan is placed on a stove, the water in the pan will boil, but not the water in the jar. Why?
29. Hydrothermal vents are openings in the ocean floor that discharge very hot water. Water emerging at nearly 280°C from one such vent off the Oregon coast, some 2400 m beneath the surface, is not boiling. Provide an explanation.
30. Water will boil spontaneously in a vacuum—on the surface of the Moon, for example. Could you cook an egg in this boiling water? Explain.
31. Our inventor friend proposes a design for cookware that will allow boiling to occur at a temperature less than 100°C so that food can be cooked with less energy consumption. Comment on this idea.
32. What can go wrong if you grasp the handle of a hot skillet with a wet thin dishcloth?
33. How can water be brought to a boil without heating it?
34. If water that boils due to reduced pressure is not hot, then is ice formed by the reduced pressure not cold? Explain.
35. Your instructor hands you a closed flask partly filled with room-temperature water. When you hold it, the heat transfer between your bare hands and the flask causes the water to boil. Quite impressive! How is this accomplished?
36. When you boil potatoes, will your cooking time be reduced with vigorously boiling water instead of gently boiling water? (Directions for cooking spaghetti call for vigorously boiling water—not to lessen cooking time but to prevent something else. If you don't know what it is, ask a cook.)
37. Why does placing a lid over a pot of water on a stove shorten the time for the water to come to a boil, whereas, after the water is boiling, the use of a lid only slightly shortens the cooking time?
38. In the power plant of a nuclear submarine, the temperature of the water in the reactor is above 100°C. How is this possible?
39. Explain why the eruptions of many geysers repeat with notable regularity.
40. Why does the water in a car radiator sometimes boil explosively when the radiator cap is removed?
41. Can ice be colder than 0°C? What is the temperature of an ice–water mixture?
42. Why is very cold ice "sticky"?
43. How does the freezing point of a liquid compare with its melting point?
44. People who live where snowfall is common will tell you that air temperatures are higher when it's snowing than when it's clear. Some misinterpret this by stating that snowfall can't occur on very cold days. Explain this misinterpretation.
45. How might water be desalinized by freezing?
46. Would regelation occur if ice crystals did not have an open structure? Explain.
47. A piece of metal and an equal mass of wood are both removed from a hot oven at equal temperatures and are dropped onto blocks of ice. The metal has a lower specific heat capacity than the wood. Which will melt more ice before cooling to 0°C?
48. How does melting ice change the temperature of the surrounding air?
49. When you step inside a warm ski lodge on a cold day, you find your eyeglasses fog. Why does this occur?
50. What accounts for the bulged ends of a can of soda that has been frozen?
51. Why is half-frozen fruit punch always sweeter than completely melted fruit punch?
52. Air-conditioning units contain no water whatever, yet it is common to see water dripping from them when they're operating on a hot day. Explain.
53. Is it condensation or vaporization that occurs on the warm outside coils of an operating air conditioner?
54. Some old-timers found that when they wrapped newspaper around the ice in their iceboxes, melting was inhibited. Discuss the advisability of this practice.
55. When ice in a pond melts, what effect does this have on the temperature of the nearby air?
56. Why is it that a tub of water placed in a farmer's canning cellar helps prevent canned food from freezing in cold winters?
57. Why will spraying fruit trees with water before a frost help to protect the fruit from freezing?
58. How can devices that heat homes in winter also be used to cool homes in summer?
59. Why does a hot dog pant?
60. Make up a multiple-choice question about evaporation and condensation energy changes.

PROBLEMS

1. The quantity of heat Q that changes the temperature ΔT of a mass m of a substance is given by $Q = cm\Delta T$, where c is the specific heat capacity of the substance. For example, for H_2O, $c = 1$ cal/g°C. And for a change of phase, the quantity of heat Q that changes the phase of a mass m is $Q = mL$, where L is the heat of fusion or heat of vaporization of the substance. For example, for H_2O, the heat of fusion is 80 cal/g (or 80 kcal/kg) and the heat of vaporization is 540 cal/g (or 540 kcal/kg). Use these relationships to determine the number of calories to change (a) 1 kg of 0°C ice to 0°C ice water, (b) 1 kg of 0°C ice water to 1 kg of 100°C boiling water, (c) 1 kg of 100°C boiling water to 1 kg of 100°C steam, and (d) 1 kg of 0°C ice to 1 kg of 100°C steam.
2. The specific heat capacity of ice is about 0.5 cal/g°C. Supposing that it remains at that value all the way to absolute zero, calculate the number of calories it would take to change a 1-g ice cube at absolute zero (−273°C) to 1 g of boiling water. How does this number of calories compare with the number of calories required to change the same gram of 100°C boiling water to 100°C steam?
3. Find the mass of 0°C ice that 10 g of 100°C steam will completely melt.
4. Consider 50 g of hot water at 80°C poured into a cavity in a very large block of ice at 0°C. What will be the final temperature of the water in the cavity? Show that 50 g of ice must melt in order to cool the hot water down to this temperature.
5. A 50-g chunk of 80°C iron is dropped into a cavity in a very large block of ice at 0°C. Show that 5.5 g of ice will melt. (The specific heat capacity of iron is 0.11 cal/g°C.)
6. If you drop a piece of ice on a hard surface, the energy of impact will melt some of the ice. The higher it drops, the more ice will melt upon impact. Show that to completely melt a block of ice that falls without air drag, it should ideally be dropped from a height of 34 km. [*Hint:* Equate the joules of gravitational potential energy to the product of the mass of ice and its heat of fusion (in SI units, 335,000 J/kg). Do you see why the answer doesn't depend on mass?]
7. A 10-kg iron ball is dropped onto a pavement from a height of 100 m. If half of the heat generated goes into warming the ball, find the temperature increase of the ball. (In SI units, the specific heat capacity of iron is 450 J/kg°C.) Why is the answer the same for a ball of any mass?
8. • The heat of vaporization of ethyl alcohol is about 200 cal/g. If 2 kg of this fluid were allowed to vaporize in a refrigerator, show that 5 kg of ice would be formed from 0°C water.

CHAPTER 17 ONLINE RESOURCES

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- Boiling Is a Cooling Process
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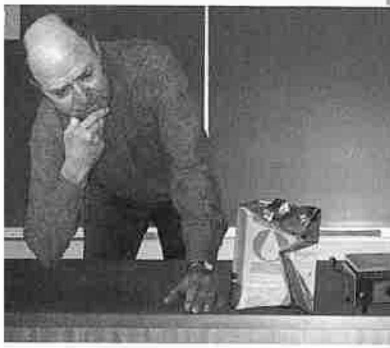
18 Thermodynamics



1 After boiling a bit of water in the gallon-size can, then sealing the can when water vapor has driven out most of the air, Dan Johnson and his class watch the can slowly crumple. By way of student discussion, the class concludes that condensation of vapor inside the can leaves a partial vacuum inside, whereupon atmospheric pressure on the outside does its thing. 2 On a larger scale, P. O. Zetterberg uses a vacuum pump to reduce the air pressure inside a 50-times larger oil drum. 3 Barbara and Tomas Brage assist as atmospheric pressure on the outside does its thing—to the applause of the class!

Lord Kelvin, for whom the Kelvin temperature scale is named, published more than 600 scientific papers and filed a total of 70 patents. He began as William Thomson, born in 1824 in Belfast, Ireland. Educated at first by his father, young Thomson began studying at the children's division of Glasgow University at age 10 after his father moved to that Scottish city. He published his first scholarly paper when he was 16. After completing studies at Glasgow, he moved on to Cambridge University and graduated with honors in 1845, at age 21. The next year he was a full professor of natural philosophy at Glasgow University. No question about it—William Thomson was a smart guy.

Among the subjects Thomson studied was heat, and in 1847 he defined the absolute temperature scale, which was subsequently named after him. He was also a strong advocate of the metric system of measurement. And in 1856, he was the first to introduce the term *kinetic energy*. He introduced Bell's telephone into Britain and helped to plan the first transatlantic cable, devising a sensitive electric meter that led to rapid transmission of Morse code signals between Europe and North America. For this success, he was knighted. The government further expressed its appreciation in 1892 by making Thomson a baron. He thenceforth was Lord Kelvin, taking his title from the Kelvin River that ran through his estate in Glasgow.

Kelvin made an estimate of the age of the Earth, a controversial subject at the time. He began his calculations by assuming that the original temperature of Earth was the temperature of the Sun. From measurements of cooling rates in rock he calculated the time for a body of Earth's size to cool. He estimated Earth's age to be about 100 million years. What Kelvin didn't know about at the time was the phenomenon of radioactivity and its role in keeping the Earth's interior warm.

Even the greatest scientists make errors and some, even worse, defend them when evidence contradicts them. Kelvin stubbornly defended his 100-million-year calculation throughout his life and contested Darwin's conclusions on evolution as impossible in the 100-million-year time period. He also said that heavier-than-air aircraft would be an impossibility. In 1900 he stated, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." Despite these serious misjudgments in his later years, his achievements in science and engineering were enormous. When he died in 1907, he was buried next to Isaac Newton in Westminster Abbey.

Thermodynamics

Kelvin was the first to coin the word **thermodynamics** (which stems from Greek words meaning "movement of heat"). The science of thermodynamics was developed in the early 19th century, before the atomic and molecular theory of matter was understood. Because the early workers in thermodynamics had only vague notions of atoms, and knew nothing about electrons and other microscopic particles, the models they used invoked macroscopic notions—such as mechanical work, pressure, and temperature—and their roles in energy transformations. The two foundation stones of thermodynamics are the conservation of energy and the fact that heat flows spontaneously from hot to cold and not the other way around. Thermodynamics provides the basic theory of heat engines, from steam turbines to nuclear reactors, and the basic theory of refrigerators and heat pumps. The laws of thermodynamics dashed the dreams of inventors and industrialists who believed in the possibility of a perpetual motion machine: a device that, upon receiving an initial input of energy, would continue to operate indefinitely without further input. We begin our study of thermodynamics with a look at one of its early concepts—a lower limit to temperature.

Absolute Zero

In principle, there is no upper limit to temperature. As thermal motion increases, a solid object first melts and then vaporizes; as the temperature is further increased, molecules break up into atoms, and atoms lose some or all of their electrons, thereby forming a cloud of electrically charged particles—a plasma. This situation exists in stars, where the temperature is many millions of degrees Celsius.

Absolute zero isn't the coldest you can *reach*. It's the coldest you can hope to approach. (Researchers have been within a billionth of a degree of it.)

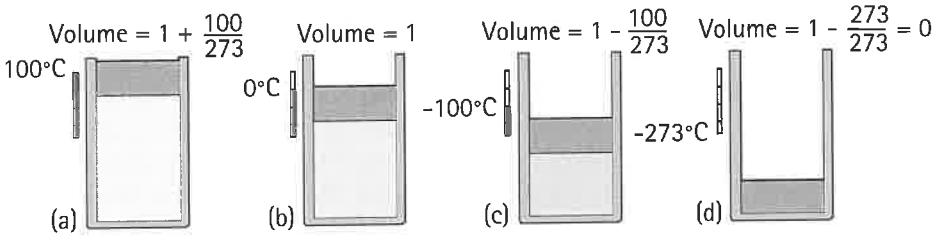
In contrast, there is a definite limit at the other end of the temperature scale. Gases expand when heated and contract when cooled. Nineteenth-century experiments found that all gases, regardless of their initial pressures or volumes, change by 1/273 of their volume at 0°C for each degree Celsius change in temperature, provided the pressure is held constant. So, if a gas at 0°C were cooled down by 273°C, it would contract, according to this rule, by 273/273 of its volume and be reduced to zero volume. Clearly, we cannot have a substance with zero volume.

Scientists also found that the pressure of any gas in any container of fixed volume changes by 1/273 of its pressure at 0°C for each degree Celsius change in temperature. So a gas in a container of fixed volume cooled to 273°C below zero would have no pressure whatsoever. In practice, every gas liquefies before it gets this cold. Nevertheless, these decreases by 1/273 increments suggested the idea of a lowest temperature: –273°C. So there is a limit to coldness.

When atoms and molecules lose all available kinetic energy, they reach the **absolute zero** of temperature. At absolute zero, as briefly discussed in Chapter 15, no more energy can be extracted from a substance and no further lowering of its temperature is possible. This limiting temperature is actually 273.15° below zero on the Celsius scale (and 459.7° below zero on the Fahrenheit scale).

FIGURE 18.1

The gray piston in the vessel goes down as the volume of gas (blue) shrinks. The volume of gas changes its volume at 0°C by 1/273 with each 1°C change in temperature when the pressure is held constant. (a) At 100°C, the volume is 100/273 greater than it is at (b), when its temperature is 0°C. (c) When the temperature is reduced to −100°C, the volume is reduced by 100/273. (d) At −273°C, the volume of the gas would be reduced by 273/273 and so would ideally be zero.



The absolute temperature scale is called the Kelvin scale, after Lord Kelvin, who first suggested this thermodynamic temperature scale. Absolute zero is 0 K (short for "0 kelvin," rather than "0 degrees kelvin"). There are no negative numbers on the Kelvin scale. Degrees on the Kelvin scale are calibrated with the same-sized divisions as on the Celsius scale. Thus, the melting point of ice is 273.15 K, and the boiling point of water is 373.15 K.

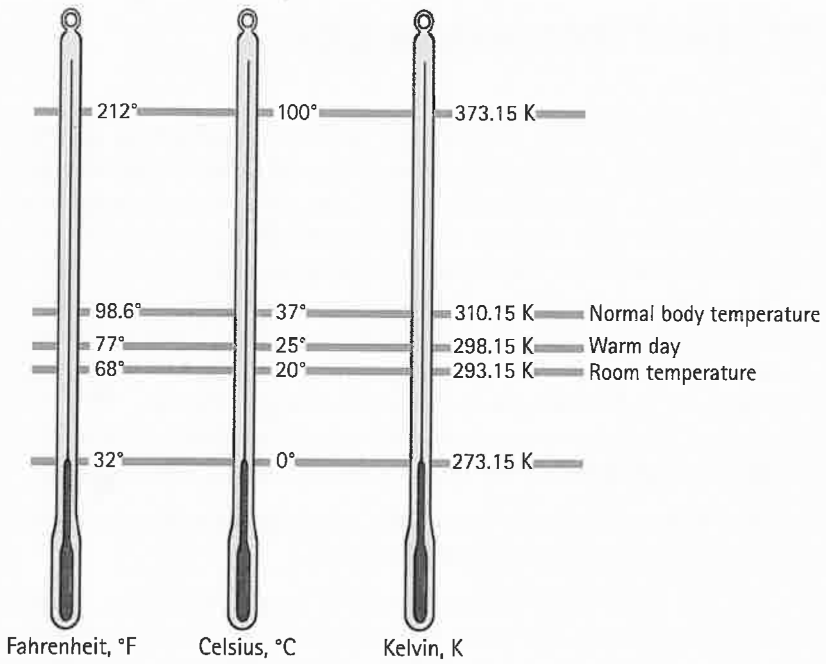


FIGURE 18.2

Familiar temperatures on different scales.

CHECK POINT

1. Which is larger, a Celsius degree or a kelvin?
2. A flask of helium gas has a temperature of 0°C. If a second, identical flask containing an equal mass of helium is twice as hot (has twice the internal energy), what is its temperature in kelvins? In degrees Celsius?

Check Your Answers

1. Neither. They are equal.
2. A container of helium twice as hot has twice the absolute temperature, or 2 times 273 K, which is 546 K. This is 273°C. (Simply subtract 273 from the Kelvin temperature to convert to Celsius degrees. Can you see why?)

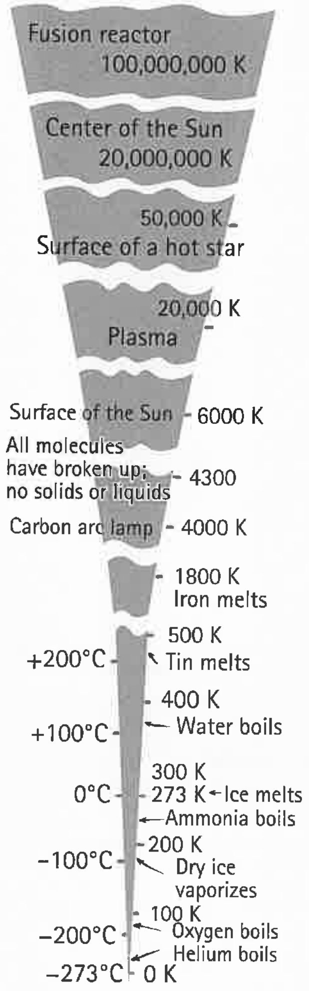


FIGURE 18.3

Some absolute temperatures.

Internal Energy

As briefly discussed in Chapter 15, there is a vast amount of energy locked in all materials. In this book, for example, the paper is composed of molecules that are in constant motion. They have kinetic energy. Due to interactions with neighboring molecules, they also have potential energy. The pages can be easily burned, so we know they store chemical energy, which is really electric potential energy at the molecular level. We know there are vast amounts of energy associated with atomic nuclei. Then there is the "energy of being," described by the celebrated equation $E = mc^2$ (mass energy). Energy at the particle level within a substance is found in these and other forms, which, when taken together, are called **internal energy.**[1] Although the internal energy in even the simplest substance can be quite complex, in our study of heat changes and heat flow we will be concerned only with the *changes* in the internal energy of a substance. Changes in temperature indicate these changes in internal energy.

First Law of Thermodynamics

Some 200 years ago, heat was thought to be an invisible fluid called *caloric,* which flowed like water from hot objects to cold objects. Caloric appeared to be conserved—that is, it seemed to flow from one place to another without being created or destroyed. This idea was the forerunner of the law of conservation of energy. By the middle of the 19th century, many years after Rumford showed that heat was not a substance locked up in matter, it was accepted that the flow of heat was nothing more than the flow of energy itself. The caloric theory of heat was gradually abandoned.[2] Today, we view heat as energy being transferred from one place to another, usually by molecular collisions. Heat is energy in transit.

When the law of energy conservation is broadened to include heat, we call it the **first law of thermodynamics.**[3] We state it generally in the following form:

> **When heat flows to or from a system, the system gains or loses an amount of energy equal to the amount of heat transferred.**

By *system,* we mean a well-defined group of atoms, molecules, particles, or objects. The system may be the steam in a steam engine or it may be Earth's entire atmosphere. It can even be the body of a living creature. The important point is that we must be able to define what is contained *within* the system and what is *outside* it. If we add heat to the steam in a steam engine, to Earth's atmosphere, or to the body of a living creature, we are adding energy to the system. The system can "use" this heat to increase its own internal energy or to do work on its surroundings. So adding heat to a system does one or both of two things: (1) it increases the internal energy of the system, if it remains in the system, or (2) it does work on things external to the system, if it leaves the system. More specifically, the first law states:

Looking for a diet plan? Consume fewer calories than you burn. This is the only diet plan firmly based on the first law of thermodynamics.

> **Heat added to a system = increase in internal energy + external work done by the system.**

The first law is an overall principle that is not concerned with the inner workings of the system itself. Whatever the details of molecular behavior in the system, the added heat either increases the internal energy of a system or enables the system to do external work (or both). Our ability to describe and predict the behavior of systems

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[1] If this book were poised at the edge of a table and ready to fall, it would possess gravitational potential energy; if it were tossed into the air, it would possess kinetic energy. But these are not examples of internal energy, because they involve more than just the particles of which the book is composed. They include gravitational interactions with Earth and motion with respect to Earth. We distinguish between the internal energy in a book and forms of external energy that may also act on the book.

[2] Popular ideas, when proved wrong, are seldom suddenly discarded. People tend to identify with the ideas that characterize their time; hence, it is often the young who are more prone to discover and accept new ideas and to push the human adventure forward.

[3] There is also a zeroth law of thermodynamics (bearing this charming name because it was formulated *after* the first and second laws were formulated), which states that two systems, each in thermal equilibrium with a third system, are in equilibrium with each other. A third law states that no system can have its absolute temperature reduced to zero.

without the need to analyze complicated atomic and molecular processes is one of the beauties of thermodynamics. Thermodynamics bridges the microscopic and macroscopic worlds.

Consider a given amount of energy supplied to a steam engine, whether in a power plant or nuclear-powered ship. The amount of energy supplied will be evident in the increased internal energy of the steam and in the mechanical work done. The sum of the increase in internal energy and the work done will equal the energy input. In no way can energy output exceed energy input. The first law of thermodynamics is simply the thermal version of the law of conservation of energy.

Adding heat to a system so the system can do mechanical work is only one application of the first law of thermodynamics. If, instead of adding heat, we do mechanical work on the system, the first law tells us what we can expect: an increase in internal energy. Rub your palms together and they become warmer. Or rub two dry sticks together and they'll certainly become hotter. Or pump the handle of a bicycle pump and the pump becomes hot. Why? Because we are primarily doing mechanical work on the system and raising its internal energy. If the process happens so quickly that very little heat is conducted out of the system, then most of the work input goes into increasing the internal energy, and the temperature rises.

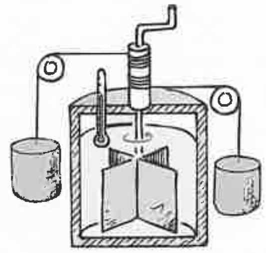

FIGURE 18.4

Paddle-wheel apparatus used to compare heat with mechanical energy. As the weights fall, they give up potential energy (mechanical), which is converted to heat that warms the water. This equivalence of mechanical and heat energy was first demonstrated by James Joule, for whom the unit of energy is named.

CHECK POINT

1. If 100 J of heat is added to a system that does no external work, by how much is the internal energy of that system raised?
2. If 100 J of heat is added to a system that does 40 J of external work, by how much is the internal energy of that system raised?

Check Your Answers

1. 100 J.
2. 60 J. We see from the first law that 100 J = 60 J + 40 J.

FIGURE 18.5

When you do work on the pump by pressing down on the piston, you compress the air inside. What happens to the temperature of the enclosed air? What happens to its temperature if it expands and pushes the piston outward?

Adiabatic Processes

Compressing or expanding a gas while no heat enters or leaves the system is said to be an **adiabatic process** (from the Greek for "impassable"). Adiabatic conditions can be achieved by thermally insulating a system from its surroundings (with Styrofoam, for example) or by performing the process so rapidly that heat has no time to enter or leave. In an adiabatic process, therefore, because no heat enters or leaves the system, the "heat added" part of the first law of thermodynamics must be zero. Then, under adiabatic conditions, changes in internal energy are equal to the work done on or by the system.[4]

For example, if we do work *on* a system by compressing it, its internal energy increases: We raise its temperature. We notice this by the warmth of a bicycle pump when air is compressed. Conversely, if work is done *by* the system, its internal energy decreases: It cools. We note this by the coolness of a tire valve if air escapes and expands from it. Rapidly expanding gas cools.

You can demonstrate the cooling of air as it expands by repeating the personal experiment of blowing air on your hand, discussed in Chapter 16. Blow air on your hand—first with your mouth wide open, then with puckered lips so the air expands (Figure 16.6, Chapter 16). Your breath is noticeably cooler when the air expands!

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Video

Adiabatic Process

As gas expands, it gives up some of its energy by doing work on its surroundings. Hence, the gas cools.

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[4] ΔHeat = Δinternal energy + work. When there is no heat transfer, ΔHeat = 0. So 0 = Δinternal energy + work. Then we can say −Work = Δinternal energy.

Meteorology and the First Law

Thermodynamics is useful to meteorologists when analyzing weather. Meteorologists express the first law of thermodynamics in the following form:

Air temperature rises as heat is added or as pressure is increased.

The temperature of the air may be changed by adding or subtracting heat, by changing the pressure of the air (which involves work), or by both. Heat is added by solar radiation, by long-wave Earth radiation, by moisture condensation, or by contact with the warm ground. An increase in air temperature results. The atmosphere may lose heat by radiation to space, by evaporation of rain falling through dry air, or by contact with cold surfaces. The result is a drop in air temperature.

There are some atmospheric processes in which the amount of heat added or subtracted is very small—small enough so that the process is nearly adiabatic. Then we have the adiabatic form of the first law:

Air temperature rises (or falls) as pressure increases (or decreases).

Adiabatic processes in the atmosphere are characteristic of parts of the air, called *parcels,* which have dimensions on the order of tens of meters to kilometers. These parcels are large enough that outside air doesn't appreciably mix with the air inside them during the minutes to hours that they exist. They behave as if they are enclosed in giant, tissue-light garment bags. As a parcel flows up the side of a mountain, its pressure lessens, allowing it to expand and cool. The reduced pressure results in reduced temperature.[5]

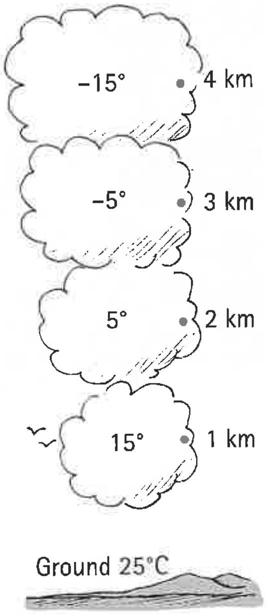

FIGURE 18.6

The temperature of a parcel of dry air that expands adiabatically decreases by about 10°C for each kilometer of elevation.

Measurements show that the temperature of a parcel of dry air will decrease by 10°C for a decrease in pressure that corresponds to an increase in altitude of 1 kilometer. So dry air cools 10°C for each kilometer it rises (Figure 18.6). Air flowing over tall mountains or rising in thunderstorms or cyclones may change elevation by several kilometers. Thus, if a parcel of dry air at ground level with a comfortable temperature of 25°C were lifted to 6 km, the temperature would be a frigid −35°C. On the other hand, if air at a typical temperature of −20°C at an altitude of 6 km descends to the ground, its temperature would be a whopping 40°C. A dramatic example of this adiabatic warming is the *chinook*—a wind that blows down from the Rocky Mountains across the Great Plains. Cold air moving down the slopes of the mountains is compressed into a smaller volume and is appreciably warmed (Figure 18.7). The effect of expansion or compression on gases is quite impressive.[6]

A rising parcel cools as it expands. But the surrounding air is cooler at increased elevations also. The parcel will continue to rise as long as it is warmer (and therefore less dense) than the surrounding air. If it gets cooler (denser) than its surroundings, it will sink. Under some conditions, large parcels of cold air sink and remain at a low level, with the result that the air above is warmer. When the upper regions of the atmosphere are warmer than the lower regions, we have a **temperature inversion.** If any rising warm air is denser than this upper layer of warm air, it will rise no farther. It is common to see evidence of this over a cold lake where visible gases and

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[5] Recall that, in Chapter 16, we treated the cooling of expanding air at the microscopic level by considering the behavior of colliding molecules. With thermodynamics, we consider only the macroscopic measurements of temperature and pressure to come up with the same results. It's nice to analyze things from more than one point of view.

[6] Interestingly enough, when you're flying at high altitudes where outside air temperature is typically −35°C, you're quite comfortable in your warm cabin—but not because of heaters. The process of compressing outside air to a cabin pressure that approximates atmospheric pressure at sea level would normally heat the air to a roasting 55°C (131°F). So air conditioners must be used to extract heat from the pressurized air.

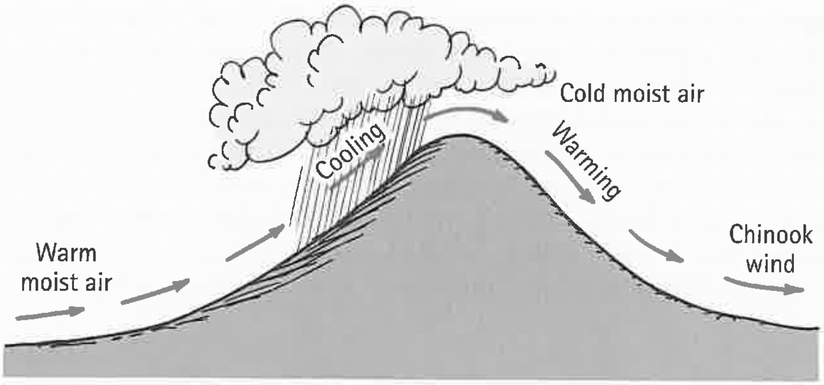

FIGURE 18.7

Chinooks, which are warm, dry winds, occur when high-altitude air descends and is adiabatically warmed.

FIGURE 18.8

A thunderhead is the result of the rapid adiabatic cooling of a rising mass of moist air. It derives energy from condensation of water vapor.

particles, such as smoke, spread out in a flat layer above the lake rather than rise and dissipate higher in the atmosphere (Figure 18.9). Temperature inversions trap smog and other thermal pollutants. The smog of Los Angeles is trapped by such an inversion, caused by low-level cold air from the ocean over which is a layer of hot air that has moved over the mountains from the hotter Mojave Desert. The mountains aid in holding the air trapped (Figure 18.10). The mountains on the edge of Denver play a similar role in trapping smog beneath a temperature inversion.[7]

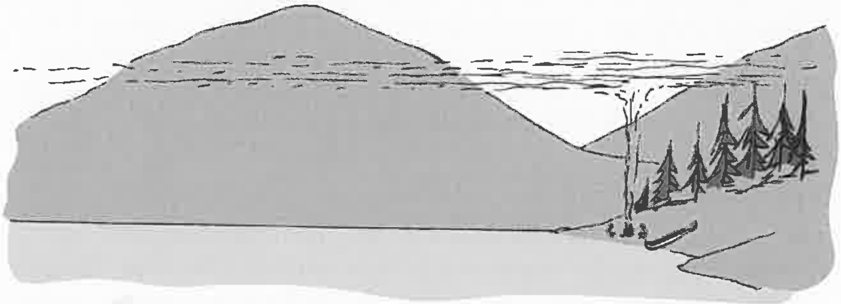

FIGURE 18.9

The layer of campfire smoke over the lake indicates a temperature inversion. The air above the smoke is warmer than the smoke, and the air below is cooler.

Adiabatic parcels are not restricted to the atmosphere, and changes in them do not necessarily happen quickly. Some deep ocean currents take thousands of years for circulation. The water masses are so huge and conductivities are so low that no appreciable quantities of heat are transferred to or from these parcels over these long periods of time. They are warmed or cooled adiabatically by changes in pressure.

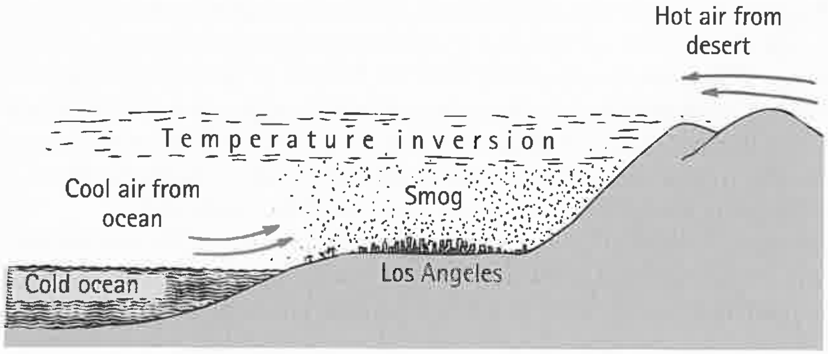

FIGURE 18.10

Smog in Los Angeles is trapped by the mountains and a temperature inversion caused by warm air from the Mojave Desert overlying cool air from the Pacific Ocean.

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[7] Strictly speaking, meteorologists call any temperature profile that thwarts upward convection a temperature inversion—including instances in which the upper regions of air are cooler but not cool enough to allow continued upward convection.

Changes in adiabatic ocean convection, as evidenced by events such as the recurring El Niño, have a great effect on Earth's climate. Ocean convection is influenced by the temperature of the ocean floor, which, in turn, is influenced by convection currents in the molten material that lies beneath Earth's crust (Figure 18.11). Knowledge of the behavior of molten material in Earth's mantle is difficult to acquire. Once a parcel of hot liquid material deep within the mantle begins to rise, will it continue to rise to Earth's crust? Or will its rate of adiabatic cooling find it cooler and denser than its surroundings, at which point it will sink? Is convection self-perpetuating? Geophysical types are currently pondering these questions.

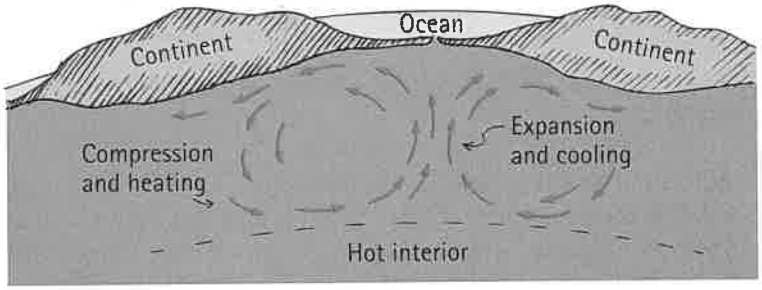

FIGURE 18.11

INTERACTIVE FIGURE

Do convection currents in the Earth's mantle drive the continents as they drift across the global surface? Do rising parcels of molten material cool faster or slower than the surrounding material? Do sinking parcels heat to temperatures above or below those of the surroundings? The answers to these questions are not known at this writing.

CHECK POINT

1. If a parcel of dry air initially at 0°C expands adiabatically while flowing upward alongside a mountain a vertical distance of 1 km, what will its temperature be? What will its temperature be when it has risen 5 km?
2. What happens to the air temperature in a valley when cold air blowing across the mountaintops descends into the valley?

Check Your Answers

1. At 1 km elevation, its temperature will be −10°C; at 5 km elevation, −50°C.
2. The air is adiabatically compressed and the temperature in the valley is increased. In this way, town residents of some valley towns in the Rocky Mountains, such as Salida, Colorado, experience "banana-belt" weather in midwinter.

fyi

- Mountaintop clouds created by forced adiabatic cooling, in effect a forced convection, is called *orographic lift* by meteorologists. These "lenticular clouds" have often been mistaken for UFOs.

Second Law of Thermodynamics

Suppose you place a hot brick next to a cold brick in a thermally insulated region. You know that the hot brick will cool as it gives heat to the cold brick, which will warm. They will arrive at a common temperature: thermal equilibrium. No energy will be lost, in accordance with the first law of thermodynamics. But pretend the hot brick extracts heat from the cold brick and becomes hotter. Would this violate the first law of thermodynamics? Not if the cold brick becomes correspondingly colder so that the combined energy of both bricks remains the same. If this were to happen, it would not violate the first law of thermodynamics.

But it would violate the **second law of thermodynamics.** The second law identifies the direction of energy transformation in natural processes. The second law of thermodynamics can be stated in many ways, but, put most simply, is

Heat of itself never flows from a cold object to a hot object.

In winter, heat flows from inside a warm, heated home to the cold air outside. In summer, heat flows from the hot air outside into the cooler interior. The direction of spontaneous heat flow is from hot to cold. Heat can be made to flow the other way from cooler to warmer, but only by doing work on the system or by adding energy from another source—as occurs with heat pumps and air conditioners, both of which cause heat to flow from cooler to warmer places.

The huge amount of internal energy in the ocean cannot be used to light a single flashlight bulb without external effort. Energy will not of itself flow from the lower-temperature ocean to the higher-temperature bulb filament. Without external effort, the direction of heat flow is *from* hot *to* cold.

CHECK POINT

Can the internal energy of a huge iceberg be harnessed to do work?

Check Your Answer

According to the second law, it can do work on cooler things, but not on warmer things. Energy spontaneously flows from hot to cold, and not the other way around.

HEAT ENGINES

Machines were the focal point of the Industrial Revolution during the late 18th and early 19th centuries. With hopes dashed for perpetual motion machines, scientists and industrialists focused on the efficiency of actual machines and the engines that drove them.

A **heat engine** is any device that converts internal energy into mechanical work. The basic idea behind a heat engine—whether a steam engine, internal combustion engine, or jet engine—is that mechanical work can be obtained only when heat flows from a high temperature to a low temperature. In every heat engine, only some of the heat can be transformed into work. In considering heat engines, we talk about *reservoirs*. Heat flows out of a high-temperature reservoir and into a low-temperature one. Every heat engine (1) gains heat from a reservoir of higher temperature, increasing the engine's internal energy; (2) converts some of this energy into mechanical work; and (3) expels the remaining energy as heat to some lower-temperature reservoir, usually called a *sink* (Figure 18.12). In a gasoline engine, for example, (1) products of burning fuel in the combustion chamber provide the high-temperature reservoir, (2) hot gases do mechanical work on the piston, and (3) heat is expelled to the environment via the cooling system and exhaust (Figure 18.13).

The second law tells us that no heat engine can convert all the heat supplied into mechanical energy. Only *some* of the heat can be transformed into work, with the

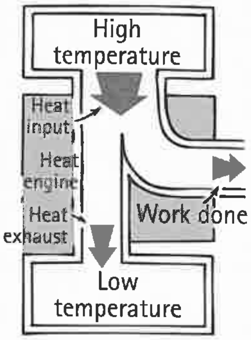

FIGURE 18.12

When heat in a heat engine flows from the high-temperature reservoir to the low-temperature sink, part of the heat can be turned into work. (If work is put into a heat engine, the flow of heat may be from the low-temperature sink to the high-temperature reservoir, as in a refrigerator or air conditioner.)

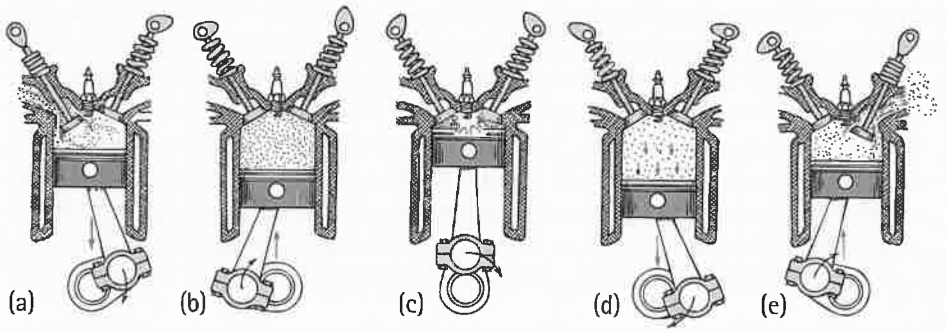

FIGURE 18.13

INTERACTIVE FIGURE

A four-cycle internal-combustion gasoline engine. (a) A fuel–air mixture fills the cylinder as the piston moves down. (b) The piston moves upward and compresses the mixture—adiabatically, because no appreciable heat is transferred in or out. (c) The spark plug fires, igniting the mixture, which raises it to a high temperature. (d) Adiabatic expansion pushes the piston downward, the power stroke. (e) The burned gases are pushed out the exhaust valve. Then the intake valve opens and the cycle repeats. These stages can be put differently: (a) suck, (b) squeeze, (c) bang, (d) push, and (e) blow.

An important source of water for a camel is not its hump but its oversized nose, which allows it to withdraw water from its own exhaled breath. Its inner nostrils are structured to recapture effectively most of the moisture contained in the warm water-saturated air moving out of its lungs.

remainder expelled in the process. Applied to heat engines, the second law may be stated:

> **When work is done by a heat engine operating between two temperatures, T_{hot} and T_{cold}, only some of the input heat at T_{hot} can be converted to work, and the rest is expelled at T_{cold}.**

Every heat engine discards some heat, which may be desirable or undesirable. Hot air expelled in a laundry or a baking oven on a cold winter day may be quite desirable, while the same hot air on a hot summer day is something else. When expelled heat is undesirable, we call it *thermal pollution.*

Before scientists understood the second law, many people thought that a very low-friction heat engine could convert nearly all the input heat energy to useful work. But not so. In 1824, the French engineer Nicolas Léonard Sadi Carnot[8] analyzed the functioning of a heat engine and made a fundamental discovery. He showed that the greatest fraction of energy input that can be converted to useful work, even under ideal conditions, depends on the temperature difference between the hot reservoir and the cold sink. Carnot's equation is

$$\text{Ideal efficiency} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}}$$

where T_{hot} is the temperature of the hot reservoir and T_{cold} is the temperature of the cold sink.[9] Ideal efficiency depends only on the temperature difference between input and exhaust. Whenever ratios of temperatures are involved, the absolute temperature scale must be used, so T_{hot} and T_{cold} are expressed in kelvins. For example, when the hot reservoir in a steam turbine is 400 K (127°C) and the sink is 300 K (27°C), the ideal efficiency is

$$\frac{400 - 300}{400} = \frac{1}{4}$$

This means that, even under ideal conditions, only 25% of the heat provided by the steam can be converted into work, while the remaining 75% is expelled as waste. This is why steam is superheated to high temperatures in steam engines and power plants. The higher the steam temperature driving a motor or turbogenerator, the higher the possible efficiency of power production. For instance, if the operating temperature in the cited example is 600 K, rather than 400 K, the efficiency would be $(600 - 300)/600 = 1/2$, which is twice the efficiency at 400 K.

The body temperature of camels can rise several degrees above normal without causing heatstroke. Their excess heat is dissipated when air temperature drops at night.

We can see the role of temperature difference between heat reservoir and sink in the operation of the steam-turbine engine in Figure 18.14. The hot reservoir is steam from the boiler and the cold sink is the exhaust region in the condenser. The hot steam exerts pressure and does work on the blades when it pushes on their front sides. This is nice. But what if the same steam pressure were also exerted on the *back side* of the blades? This would be counterproductive and not so nice. It is vital that pressure on the back side of the blades be reduced. How is it done? The same way that pressure inside the can of steam is reduced in the Thermodynamics Dramatized! Box on page 325. If you condense the steam, the pressure on the blades' back sides is greatly reduced. We know that, with confined steam, temperature and pressure go hand in hand: Increase

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[8] Carnot was the son of Lazare Nicolas Marguerite Carnot (pronounced car-no), who created the fourteen armies after the revolution that defended France against all of Europe. After his defeat at Waterloo, Napoleon said to Lazare, "Monsieur Carnot, I came to know you too late." A few years after producing his famous equation, Nicolas Léonard Sadi Carnot died tragically at the age of 36 during a cholera epidemic that swept through Paris.

[9] Efficiency = work output/heat input. From energy conservation, heat input = work output + heat that flows out at low temperature (see Figure 18.12). So work output = heat input – heat output. So efficiency = (heat input – heat output)/(heat input). In the ideal case, it can be shown that the ratio (heat out)/(heat in) = $T_{\text{cold}}/T_{\text{hot}}$. Then we can say ideal efficiency = $(T_{\text{hot}} - T_{\text{cold}})/T_{\text{hot}}$.

Thermodynamics Dramatized!

Put a small amount of water in an aluminum soda-pop can and heat it on a stove until steam issues from the opening. When this occurs, air has been driven out and replaced by steam. Then, with a pair of tongs, quickly invert the can into a pan of water. Crunch! The can is crushed by atmospheric pressure! Why? When the molecules of steam encounter water from the pan, condensation occurs, leaving a very low pressure in the can, whereupon the surrounding atmospheric pressure crunches the can. Here we see, dramatically, how pressure is reduced by condensation. Can you now better understand the role of condensation in the turbine of Figure 18.14?

temperature and you increase pressure; decrease temperature and you decrease pressure. So the pressure difference necessary for the operation of a heat engine is directly related to the temperature difference between source and sink. The greater the temperature difference, the greater the efficiency.[10]

Carnot's equation states the upper limit of efficiency for all heat engines, whether in an automobile, a nuclear-powered ship, or a jet aircraft. In practice, friction is always present in all engines, and efficiency is always less than ideal.[11] So, whereas friction is solely responsible for the inefficiencies of many devices, the overriding concept in the case of heat engines is the second law of thermodynamics: Only some of the heat input can be converted to work—even without friction.

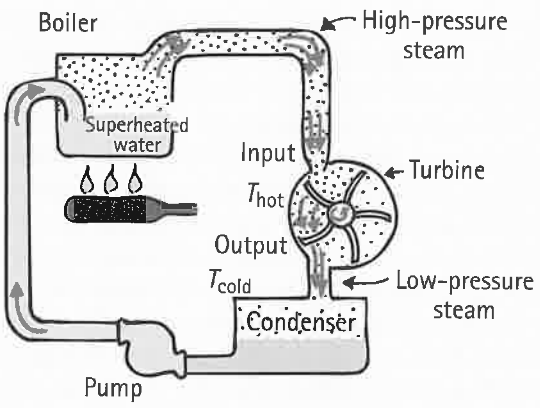

FIGURE 18.14

The steam cycle. The turbine turns because pressure exerted by high-temperature steam on the front side of the turbine blades is greater than that exerted by low-temperature steam on the back side of the blades. Without a pressure difference, the turbine would not rotate and deliver energy to an external load (such as an electric generator). The presence of steam pressure on the back side of the blades, even without friction, prevents the turbine from being a perfectly efficient engine.

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[10] Physicist Victor Weisskopf tells the story of an engineer who is explaining the operation of a steam engine to a peasant. The engineer explains in detail the engine's steam cycle, whereupon the peasant asks, "Yes, I understand all that, but where's the horse?" It's difficult to abandon our way of looking at the world when a newer method comes along to replace established ways.

[11] The ideal efficiency of an automobile internal-combustion engine is more than 50%, but, in practice, the actual efficiency is about 25%. Engines of higher operating temperatures (compared to sink temperatures) would be more efficient, but the melting point of engine materials limits the upper temperatures at which they can operate. Higher efficiencies await engines made with new materials with higher melting points. Keep your eyes on ceramic engines!

CHECK POINT

1. What would be the ideal efficiency of an engine if its hot reservoir and exhaust were the same temperature—say, 400 K?
2. What would be the ideal efficiency of a machine having a hot reservoir at 400 K and a cold reservoir somehow maintained at absolute zero?

Check Your Answers

1. Zero efficiency: $(400 - 400)/400 = 0$. So no work output is possible for any heat engine unless a temperature difference exists between the reservoir and the sink.
2. One: $(400 - 0)/400 = 1$. Only in this idealized case is an ideal efficiency of 100% possible.

FIGURE 18.15

The Transamerica Pyramid and some other buildings are heated by electric lighting, which is why the lights are on most of the time.

Order Tends to Disorder

The first law of thermodynamics states that energy can neither be created nor destroyed. It speaks of the *quantity* of energy. The second law qualifies this by adding that the form energy takes in transformations "deteriorates" to less useful forms. It speaks of the *quality* of energy, as energy disperses and ultimately degenerates into waste. Another way to say this is that organized energy (concentrated, and therefore usable, high-quality energy) degrades into disorganized energy (nonusable, low-quality energy). For example, once water flows over a waterfall, it loses its potential for useful work. Similarly for gasoline, where organized energy degrades as it burns in a car engine. Useful energy degrades to nonuseful forms and is unavailable for doing the same work again, such as driving another car engine. Heat, dispersed into the environment as thermal energy, is the graveyard of useful energy.

The quality of energy is lowered with each transformation, as energy of an organized form tends to degrade into disorganized forms. With this broader perspective, the second law can be stated another way:

In natural processes, high-quality energy tends to transform into lower-quality energy—order tends toward disorder.

FIGURE 18.16

Molecules of perfume readily go from the bottle (a more ordered state) to the air (a less ordered state), and not vice versa.

Consider a system consisting of a stack of pennies on a table, all heads up. Somebody walks by and accidentally bumps the table and the pennies topple to the floor, certainly not landing all heads up. Order becomes disorder. Molecules of gas all moving in harmony make up an orderly state—and also an unlikely state. On the other hand, molecules of gas moving in haphazard directions with a broad range of speeds make up a disorderly, chaotic (and more likely) state. If you remove the lid of a perfume bottle or open the oven door on a tray of baked chocolate cookies, molecules escape into the room and make up a more disorderly state. Relative order becomes disorder. You would not expect the reverse to happen by itself; that is, you would not expect the perfume or cookie molecules to spontaneously order themselves back into the bottle or tray and thereby return to the more ordered state.

FIGURE 18.17

If you push a crate full of auto parts across a rough floor, all your work goes into heating the floor and the crate. Work against friction produces heat, which cannot do any work on the crate. Ordered energy is transformed into disordered energy.

Processes in which disorder returns to order without any external help don't occur in nature. Interestingly, time is given a direction via this thermodynamic rule. Time's arrow always points from order to disorder.[12]

Disordered energy can be changed to ordered energy only with organizational effort or work input. For example, water in a refrigerator freezes and becomes more

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[12] Reversible systems look sensible when a movie film of them is run backward. Remember those old movies where a train comes to a stop inches away from a heroine tied to the tracks? How was this done without mishap? Simple. The train began at rest, inches away from the heroine, and went *backward*, gaining speed. When the film was reversed, the train was seen to move *toward* the heroine. Watch closely for the telltale smoke that *enters* the smokestack!

ordered because work is put into the refrigeration cycle; gas can be ordered into a small region if a compressor supplied with outside energy does work. Processes in which the net effect is an increase in order always require an external input of energy. But, for such processes, there is always an increase of disorder somewhere else to more than offset the increase of order.

Biological systems are enormously complex and, while living, never reach thermal equilibrium.

CHECK POINT

In your bedroom are probably some 10^{27} air molecules. If they were all to congregate on the opposite side of the room, you could suffocate. But this is unlikely. Is such a spontaneous congregation of molecules less likely, more likely, or of the same probability if there are fewer molecules in the room?

Check Your Answer

Fewer molecules mean a greater probability of their spontaneously congregating on the opposite side of your room. Exaggeration makes this credible: If there is only one molecule in the room, there's a 50% chance of it being in the other half of the room. If you have two molecules, the chances of both being on one side at the same time is 25%. If there are three molecules, the chance of your being breathless is one-eighth (12.5%). The greater the number of molecules, the greater the chances of there being nearly equal numbers of molecules on both sides of the room.

Sharks rely on a gel under their skin that detects extremely small changes in ocean temperature—less than a thousandth of a degree Celsius. This capability likely assists in detecting subtle temperature boundaries where their prey are found.

Entropy

Energy tends to disperse: Hot air in a hot oven disperses when an oven door is opened. Energy tends to degrade: Energy locked in chemical bonds of wood degrades when the wood is burned. **Entropy** is the term we use to describe the natural dispersing or degrading of energy. Entropy can be measured by the *amount of disorder* in a system.[13] More entropy means more dispersal or more degradation of energy. Since energy tends to disperse and degrade with time, the total amount of entropy in any system tends to increase with time. Whenever a physical system is allowed to distribute its energy freely, it always does so in a manner such that entropy increases while the energy of the system remaining available for doing work decreases.

The net entropy in the universe is continually increasing (continually running "downhill"). We say *net* because there are some regions in which energy is actually being organized and concentrated. This occurs in living organisms, which survive by concentrating and organizing energy from food sources. All living organisms, from bacteria to trees to human beings, extract energy from their surroundings and use it to increase their own organization (growth and repair). In living organisms, entropy decreases. But the order in life forms is maintained by increasing entropy elsewhere, resulting in a net increase in entropy. Energy must be transformed into the living system to support life. When it isn't, the organism soon dies and tends toward disorder.[14]

The first law of thermodynamics is a universal law of nature to which no exceptions have been observed. The second law, however, is a probabilistic statement.

FIGURE 18.18
Entropy.

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[13] Entropy can be expressed mathematically. The increase in entropy ΔS of a thermodynamic system is equal to the amount of heat added to the system ΔQ divided by the temperature T at which the heat is added: $\Delta S = \Delta Q/T$.

[14] Interestingly enough, the American writer Ralph Waldo Emerson, who lived during the time the second law of thermodynamics was the new science topic of the day, philosophically speculated that not everything becomes more disordered with time and cited the example of human thought. Ideas about the nature of things grow increasingly refined and better organized as they pass through the minds of succeeding generations. Human thought is evolving toward more order.

Old riddle: "How do you unscramble an egg?" Answer: "Feed it to a chicken." But even then you won't get your original egg back. Making eggs takes energy and increases entropy.

Given enough time, even the most improbable states may occur; entropy may sometimes decrease. For example, the haphazard motions of air molecules could momentarily become harmonious in a corner of the room, just as a tall stack of pennies spilled on the floor could all come up heads. These situations are possible, but they are not probable. The second law tells us the most probable course of events, not the only possible one.

The laws of thermodynamics are often stated this way: You can't win (because you can't get any more energy out of a system than you put into it), you can't break even (because you can't get as much useful energy out as you put in), and you can't get out of the game (entropy in the universe is always increasing).

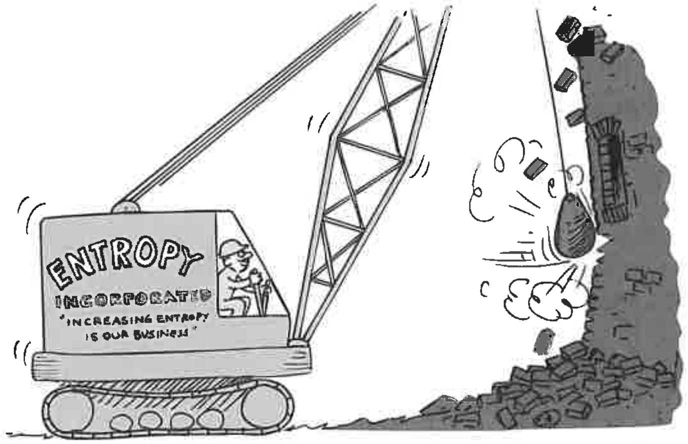

FIGURE 18.19
Why is the motto of this contractor—"Increasing entropy is our business"—so appropriate?

SUMMARY OF TERMS

Thermodynamics The study of heat and its transformation to different forms of energy.

Absolute zero The lowest possible temperature that a substance may have; the temperature at which particles of a substance have their minimum kinetic energy.

Internal energy The total energy (kinetic plus potential) of the submicroscopic particles that make up a substance. *Changes* in internal energy are of principal concern in thermodynamics.

First law of thermodynamics A restatement of the law of energy conservation, applied to systems in which energy is transferred by heat and/or work. The heat added to a system equals its increase in internal energy plus the external work it does on its environment.

Adiabatic process A process, often of fast expansion or compression, wherein no heat enters or leaves a system.

Temperature inversion A condition in which upward convection of air ceases, often because an upper region of the atmosphere is warmer than the region below it.

Second law of thermodynamics Thermal energy never spontaneously flows from a cold object to a hot object. Also, no machine can be completely efficient in converting heat to work; some of the heat supplied to the machine at high temperature is dissipated as waste heat at lower temperature. And finally, all systems tend to become more and more disordered as time goes by.

Heat engine A device that uses heat as input and supplies mechanical work as output, or that uses work as input and moves heat "uphill" from a cooler to a warmer place.

Entropy A measure of the disorder of a system. Whenever energy freely transforms from one form to another, the direction of transformation is toward a state of greater disorder and therefore toward one of greater entropy.

REVIEW QUESTIONS

Thermodynamics

1. What is the origin and meaning of the word *thermodynamics?*
2. Is the study of thermodynamics concerned primarily with microscopic processes or with macroscopic ones?

Absolute Zero

3. By how much does the volume of gas at 0°C contract for each decrease in temperature of 1 Celsius degree when the pressure is held constant?

4. By how much does the pressure of gas at 0°C decrease for each decrease in temperature of 1 Celsius degree when the volume is held constant?
5. If we assume the gas does not condense to a liquid, what volume is approached for a gas at 0°C cooled by 273 Celsius degrees?
6. What is the lowest possible temperature on the Celsius scale? On the Kelvin scale?

Internal Energy

7. What else besides molecular kinetic energy contributes to the internal energy of a substance?
8. Is the principal concern in the study of thermodynamics the *amount* of internal energy in a system or the *changes* in internal energy in a substance?

First Law of Thermodynamics

9. How does the law of the conservation of energy relate to the first law of thermodynamics?
10. What is the relationship between heat added to a system, change in its internal energy, and external work done by the system?
11. What happens to the internal energy of a system when mechanical work is done on it? What happens to its temperature?

Adiabatic Processes

12. What condition is necessary for a process to be adiabatic?
13. If work is done *on* a system, does the internal energy of the system increase or decrease? If work is done *by* a system, does the internal energy of the system increase or decrease?

Meteorology and the First Law

14. How do meteorologists express the first law of thermodynamics?
15. What is the adiabatic form of the first law?
16. What generally happens to the temperature of rising air? Of sinking air?
17. What is a temperature inversion?
18. Do adiabatic processes apply only to gases? Defend your answer.

Second Law of Thermodynamics

19. How does the second law of thermodynamics relate to the direction of heat flow?

Heat Engines

20. What three processes occur in every heat engine?
21. What exactly is thermal pollution?
22. How does the second law relate to heat engines?
23. Why is the condensation part of the cycle in a steam turbine so essential?

Order Tends to Disorder

24. Distinguish between high-quality energy and low-quality energy in terms of organized and disorganized energy. Give an example of each.
25. How can the second law be stated with regard to high-quality and lower-quality energy?
26. With respect to orderly and disorderly states, what do natural systems tend to do? Can a disorderly state ever transform to an orderly state? Explain.

Entropy

27. What is the physicist's term for *measure of amount of disorder?*
28. Distinguish between the first and second laws of thermodynamics in terms of whether or not exceptions occur.

EXERCISES

1. A friend said the temperature inside a particular oven is 500 and the temperature inside a particular star is 50,000. You're unsure whether your friend meant Celsius degrees or kelvins. How much difference does it make in each case?
2. The temperature of the Sun's interior is about 10^7 degrees. Does it matter whether this is degrees Celsius or kelvins? Explain.
3. When heat flows from a warm object in contact with a cool object, do both objects undergo the same amount of temperature change?
4. Heat always flows spontaneously from an object with a higher temperature to an object with a lower temperature. Is this the same thing as saying that heat always flows from an object with a greater internal energy to one with a lower internal energy? Explain.
5. Consider a jar of helium with a temperature of 0°C. What will be its temperature if it is twice as hot (has twice the internal energy)?
6. If you vigorously shake a can of chicken broth back and forth for more than a minute, will the temperature of the broth increase? (Try it and see.)
7. When air is quickly compressed, why does its temperature increase?
8. Suppose you do 100 J of work in compressing a gas. If 80 J of heat escapes in the process, what is the change in internal energy of the gas?
9. Why does the bottom of a tire pump feel hot when you pump air in the tire, but when air is released, the valve stem feels cool?
10. When you blow up a balloon, do you slightly warm the balloon? When air is allowed to rush out of it, how, if at all, does the temperature of that expanding air change?
11. What happens to the gas pressure within a sealed gallon can when it is heated? When it is cooled? Why?
12. Is it possible to wholly convert a given amount of mechanical energy into thermal energy? Is it possible to wholly convert a given amount of thermal energy into mechanical energy? Cite examples to illustrate your answers.
13. Why does cold mountain air become warm when it descends into a valley?
14. Everybody knows that warm air rises. So it might seem that the air temperature should be higher at the tops of

mountains than down below. But the opposite is most often the case. Why?

15. What is the ultimate source of energy in coal, oil, and wood? Why do we call energy from wood renewable but energy from coal and oil nonrenewable?

16. What is the ultimate source of energy in a hydroelectric power plant?

17. The combined molecular kinetic energies of molecules in a cool lake are greater than the combined molecular kinetic energies of molecules in a cup of hot tea. Pretend you partially immerse the teacup in the lake and that the tea *absorbs* 10 calories from the water and becomes hotter, while the water that gives up 10 calories becomes cooler. Would this energy transfer violate the first law of thermodynamics? The second law of thermodynamics? Defend your answers.

18. Why is thermal pollution a relative term?

19. The box "Thermodynamics Dramatized" shows the crushing of an inverted steam-filled can placed in a pan of water. Would the water need to be cold? Would crushing occur if the water were hot but not boiling? Would it crush in boiling water? (Try it and see!)

20. Why is it advantageous to use steam that is as hot as possible in a steam-driven turbine?

21. How does the ideal efficiency of an automobile relate to the temperature of the engine and the temperature of the environment in which it operates? Be specific.

22. What happens to the efficiency of a heat engine when the temperature of the reservoir into which thermal energy is transferred is lowered?

23. Under what conditions would a heat engine be 100% efficient?

24. To increase the efficiency of a heat engine, would it be preferable to produce the same temperature increment by increasing the temperature of the reservoir while maintaining the temperature of the sink constant, or to decrease the temperature of the sink while maintaining the temperature of the reservoir constant? Explain.

25. Could you cool a kitchen by leaving the refrigerator door open and closing the kitchen door and windows? Explain.

26. Could you warm a kitchen by leaving the door of a hot oven open? Explain.

27. An electric fan not only doesn't decrease the temperature of air, but it actually increases air temperature. How, then, are you cooled by a fan on a hot day?

28. Strictly speaking, why will a refrigerator containing a fixed amount of food consume more energy in a warm room than in a cold room?

29. A refrigerator moves heat from cold to warm. Why does this not violate the second law of thermodynamics?

30. What happens to the density of a quantity of gas when its temperature is decreased and its pressure is held constant?

31. If you squeeze an air-filled balloon and no heat escapes, what happens to the internal energy of the gas in the balloon?

32. In buildings that are being electrically heated, is it at all wasteful to turn all the lights on? Is turning all the lights on wasteful if the building is being cooled by air-conditioning?

33. Why can the drinking bird in Figure 17.4 in the previous chapter be considered a heat engine?

34. Defend the statement that 100% of the electrical energy that goes into lighting a lamp is converted to thermal energy. Are the first and the second laws of thermodynamics violated?

35. Molecules in the combustion chamber of a rocket engine are in a high state of random motion. When the molecules are expelled through a nozzle in a more ordered state, will their temperature be more, less, or the same as their initial temperature in the chamber before being exhausted?

36. Is the total energy of the universe becoming more unavailable with time? Explain.

37. According to the second law of thermodynamics, is the universe moving to a more ordered state or to a more disordered state?

38. Do adiabatic parcels occur in the atmosphere, in the ocean, or in both?

39. The ocean possesses enormous numbers of molecules, all with kinetic energy. Can this energy be extracted and used as a power source? Defend your answer.

40. Why do we say a substance in a liquid phase is more disordered than the same substance in a solid phase?

41. Comment on this statement: The second law of thermodynamics is one of the most fundamental laws of nature, yet it is not an exact law at all.

42. Water evaporates from a salt solution and leaves behind salt crystals that have a higher degree of molecular order than the more randomly moving molecules in the saltwater. Has the entropy principle been violated? Why or why not?

43. Water put into the freezer compartment of your refrigerator goes to a state of less molecular disorder when it freezes. Is this an exception to the entropy principle? Explain.

44. As a chicken develops from an egg, it becomes more ordered with time. Does this violate the principle of entropy? Explain.

45. The United States Patent and Trademark Office rejects claims for perpetual motion machines (in which energy output is as great or greater than energy input) without even investigating them. Why is this?

46. It is generally assumed that perpetual motion machines are impossible to construct. Is it inconsistent to say that molecules are in perpetual motion?

47. A classmate says that all this stuff about no perpetual motion is bunk; that atoms, planets, stars, and everything are in perpetual motion. What distinction is being missed here?

48. (a) If you spent 10 minutes repeatedly shaking and throwing down a pair of coins, would you expect to see two heads come up at least once? (b) If you spent an hour shaking a handful of 10 coins and throwing them down, would you expect to see all 10 come up heads at least once? (c) If you stirred a box of 10,000 coins and tossed them repeatedly on the floor all day long, would you expect to see all 10,000 appear as heads at least once?

PROBLEMS

1. What is the ideal efficiency of an automobile engine in which fuel is heated to 2700 K and the outdoor air is 270 K?
2. Consider an ocean thermal energy conversion (OTEC) power plant that operates on a temperature difference between deep 4°C water and 25°C surface water. Show that the Carnot efficiency of this plant is 7%.
3. On a chilly 10°C day, your friend who loves cold weather says she wishes it were twice as cold. Taking this literally, show that the temperature she wishes for would be −131.5°C.
4. Imagine a giant dry-cleaner's bag full of air at a temperature of −35°C floating like a balloon with a string hanging from it 10 km above the ground. Estimate what its temperature would be if you were able to yank it suddenly back to Earth's surface.
5. Calculate the ideal efficiency of an engine wherein fuel is heated to 2700 K and the surrounding air is 300 K.
6. Wally Whacko claims to have invented a heat engine that will revolutionize industry. It runs between a hot source at 300°C and a cold sink at 25°C. He claims that his engine is 92% efficient.
   (a) What error did he make in his choice of temperature scales?
   (b) What is the actual maximum efficiency of his engine?
7. A power station with an efficiency of 0.4 generates 10^8 W of electric power and dissipates 1.5×10^8 J of heat energy each second to the cooling water that flows through it, which increases its temperature by 3 Celsius degrees. Knowing that the specific heat of water in SI units is 4184 J/kg·°C, show that 12,000 kg of warmed water flows through the plant each second.

• **8.** Construct a table of all the possible combinations of numbers that can come up when you throw two dice. Your friend says, "Yes, I know that 7 is the most likely total number when two dice are thrown. But *why* 7?" Based on your table, answer your friend, and explain that, in thermodynamics, the situations that are likely to be observed are those that can be formed in the greatest number of ways.

CHAPTER 18 ONLINE RESOURCES

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PART THREE MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following.

1. Temperature is generally proportional to a substance's
   (a) thermal energy.
   (b) vibrational kinetic energy.
   (c) average translational kinetic energy.
   (d) rotational kinetic energy.
2. Heat is simply another word for
   (a) temperature.
   (b) internal energy.
   (c) internal energy that flows from hot to cold.
   (d) radiant energy.
3. Which of these temperatures is likely when a container of water at 20°C is mixed with water at 28°C?
   (a) 19°C. (c) 30°C.
   (b) 22°C. (d) More than 30°C.
4. The amount of heat transferred to a system can be measured in
   (a) calories. (c) Either.
   (b) joules. (d) Neither.
5. Hot sand cools off faster at night than vegetation. Compared with vegetation, sand's specific heat capacity is
   (a) less. (c) about the same.
   (b) greater. (d) Can't say.
6. When the temperature of a strip of iron is increased, the length of the strip
   (a) also increases.
   (b) actually decreases.
   (c) may increase and may decrease.
   (d) decreases in width as it gets longer.
7. Microscopic slush in water tends to make the water
   (a) more dense. (c) more slippery.
   (b) less dense. (d) warmer.
8. The principal source of Earth's internal energy is
   (a) tidal friction. (c) radioactivity.
   (b) gravitational pressure. (d) geothermal heat.
9. The surface of planet Earth loses energy to outer space due mostly to
   (a) conduction. (c) radiation.
   (b) convection. (d) radioactivity.
10. The greenhouse gases that contribute to global warming are
    (a) water vapor. (c) Both.
    (b) carbon dioxide. (d) Neither.
11. In a mixture of hydrogen, oxygen, and nitrogen gases at a given temperature, the fastest molecules on average are those of
    (a) hydrogen. (c) nitrogen.
    (b) oxygen. (d) All have same average speed.
12. Thermal conduction mainly involves
    (a) electrons. (c) neutrons.
    (b) protons. (d) ions.
13. Thermal convection mainly involves
    (a) radiant energy. (c) insulators.
    (b) fluids. (d) All of these.
14. Heat comes from the Sun to Earth by the process of
    (a) conduction.
    (b) convection.
    (c) radiation.
    (d) All of these, though radiation is greater.
15. A high-temperature source radiates relatively
    (a) short wavelengths. (c) low frequencies of radiation.
    (b) long wavelengths. (d) None of these.
16. An object that absorbs energy well also
    (a) conducts well. (c) radiates well.
    (b) convects well. (d) None of these.
17. Newton's law of cooling applies to objects that
    (a) cool. (c) Both.
    (b) warm up. (d) Neither.
18. Compared with radiation from the Sun, terrestrial radiation has a lower
    (a) wavelength. (c) Both.
    (b) frequency. (d) Neither.
19. When relatively slow-moving molecules condense from the air, the temperature of the remaining air tends to
    (a) remain unchanged. (c) increase.
    (b) decrease. (d) spread out uniformly.
20. Put a saucer of water on your table. A process that then occurs is
    (a) evaporation. (c) Both.
    (b) condensation. (d) Neither.
21. The process of boiling water tends to
    (a) warm the water. (c) Both.
    (b) cool the water. (d) Neither.
22. Boiling and freezing occur when water is subjected to
    (a) decreased temperatures.
    (b) decreased atmospheric pressure.
    (c) increased temperatures.
    (d) increased atmospheric pressure.
23. Regelation occurs due to water's
    (a) high specific heat.
    (b) open-structured ice crystals.
    (c) high rate of expansion.
    (d) slight tendency to freeze when temperature is lowered.
24. When water changes to steam, energy is
    (a) absorbed by the water.
    (b) released by the water.
    (c) conserved as the phase change occurs.
    (d) changed to a different form.
25. The lowest possible temperature is absolute zero, at
    (a) 0 kelvin. (c) Both are the same.
    (b) −273°C. (d) None of these.
26. When you breathe on your hand, the temperature of the exhaled air reaching your hand
    (a) increases. (c) remains unchanged.
    (b) decreases. (d) depends on how you blow.
27. The second law of thermodynamics tells us that heat doesn't flow from
    (a) hot to cold ever.
    (b) cold to hot ever.
    (c) hot to cold without external energy.
    (d) cold to hot without external energy.
28. Heat engines, such as a jet engine, are more efficient when run at
    (a) high temperatures.
    (b) constant temperatures.
    (c) low temperatures.
    (d) a constant rate.
29. The direction of natural processes is from states of
    (a) higher order to lower order.
    (b) lower order to higher order.
    (c) disorganization to organization.
    (d) disorder to equilibrium.
30. As entropy in a system increases, energy in the system
    (a) becomes more ordered.
    (b) becomes less ordered.
    (c) reaches equilibrium.
    (d) moves toward destruction.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.